COLLECTION AND PRELIMINARY ANALYSIS OF UNDER-ICE AMBIANT NOISE DATA, CAPE NORTH, JANUARY TO APRIL 1971

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THESIS

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by

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September 1971

Collection and Preliminary Analysis of Under-Ice Ambient Noise Data, Cape North, January to April 1971

by

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ABSTRACT

Ambient noise data was collected from bottom-mounted hydrophones in 65 fms of water near Cape North, Nova Scotia, from January to April 1971. Preliminary analyses indicate that generalizations made from data collected at other sites can be used in only the broadest sense to predict noise levels at Cape North. The open water spectral shapes resemble deep water spectral shapes proposed by Wenz (1962) rather than shallow water spectra found by Piggott (1964) at another location on the Scotian Shelf. Under-ice noise levels are below open water levels in the frequency range 40 Hz to 2 kHz, but above this frequency, mechanical noise sources within the ice pack elevate levels above those found under open water conditions.

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ACKNOWLEDGEMENT

Dr. Warren W. Denner, Associate Professor of Oceanography, Naval Postgraduate School, suggested this research project and was instrumental in organizing and directing it. Dr. Anthony Eller, Assistant Professor of Physics, Naval Postgraduate School, willingly provided advice and equipment which facilitated the analysis phase of the investigation. The Naval Ordnance Laboratory, White Oak, Maryland, and the Defence Research Establishment Atlantic, Dartmouth, Nova Scota, provided logistic and technical support during the field investigations.

I. INTRODUCTION

The Knudsen curves published in 1944 [Ref. 1] were among the first printed data on underwater ambient noise. A summary of ambient noise studies was published by Wenz in 1962 [Ref. 2]. However, it made only cursory mention of the effect ice cover had on the ambient noise spectrum.

During the last few years acoustic and environmental investigations have extended into ice-covered regions of the oceans. Installation of an Under Ice Acoustic Research Station was completed in September 1970 near Cape North, Nova Scotia. The facility, a joint Canadian-United States project, consists of four underwater arrays; terminal equipment for three of the arrays is located in a Naval Ordnance Laboratory (NOL) trailer, and an adjoining building houses terminal equipment for the Canadian Defence Research Board array as well as environmental sensors used in this study (Figure 1).

The Cape North area is unique in that it presents a wide range of ice cover conditions during a relatively short ice season. The ice pattern has been observed to change from consolidated pack to loose pack and then to open water over a period of 24 hours. This change was the result of a change in wind direction. Strong tidal currents flowing between the Gulf of St. Lawrence and the Cabot Strait cause significant ice movement even in conditions of consolidated pack ice.

Figure 1. Drawing of Cape North Acoustic Range showing locations of NOL and ARL arrays.

Two experimental acoustical systems are operated from the NOL terminal:

1. An active and passive system designed by the Applied Research Laboratory, University of Texas (ARL) for high-frequency reverberation and noise studies.

2. A NOL designed passive system capable of monitoring signals from 30 Hz to 60 kHz.

Research reported in this study was conducted with the NOL system; the ARL system was operated on a non-interference basis and the data has been forwarded to the Applied Research Laboratory for separate analysis. The purpose of the project was twofold:

1. To evaluate the system's performance by comparing results with those obtained by other workers under similar conditions.

2. To extend the under-ice ambient noise above 10 kHz, since very little previous data has been reported above this limit.

II. SUMMARY OF AMBIENT SEA NOISE CHARACTERISTICS

A. AMBIENT NOISE WITHOUT ICE COVER

The surveys by Wenz (1962) and Urick (1969) provide useful references for average ambient noise levels. They also enumerate sources that cause noise levels to deviate from the average. Both authors agree that noise spectrum between 0 and 100,000 Hz may be divided into bands, with the level in each band being principally a function of a different variable.

Urick divides the deep ocean spectrum into five bands (Figure 2).

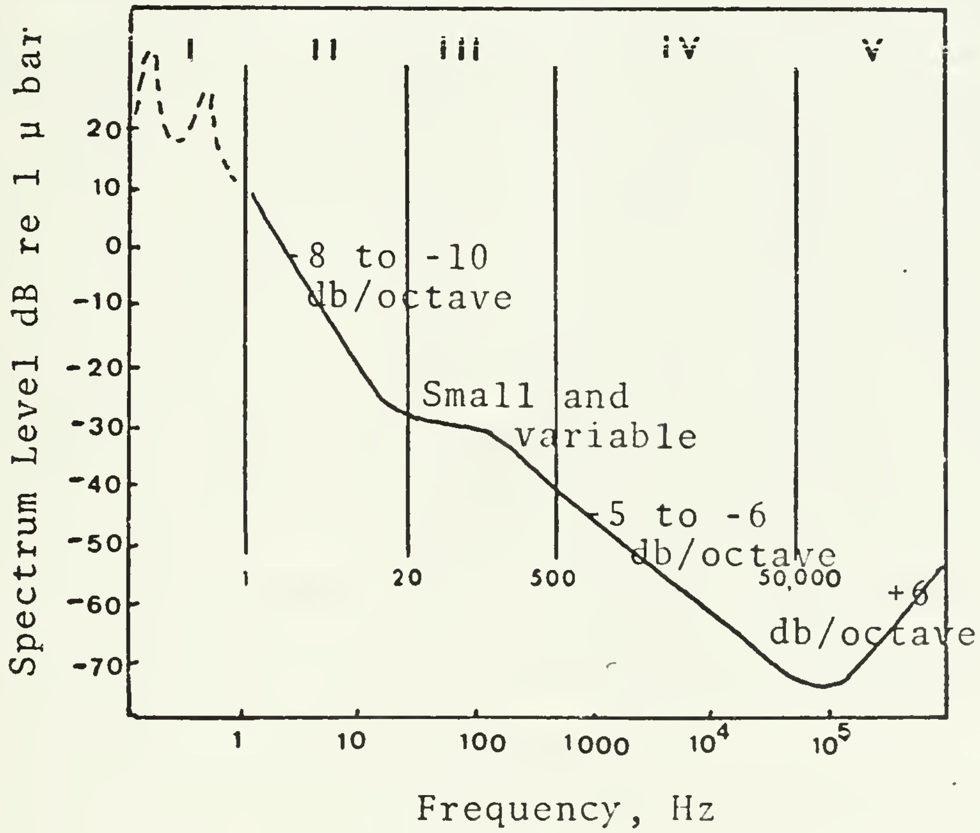


Figure 2. Average deep water ambient noise spectrum (after Urick, 1969)

Band I is the least known portion; it lies below 1 Hz and the noise appears to originate from hydrostatic and

seismic sources. Band II is characterized by a slope of -8 to -10 dB/octave. The primary noise source is oceanic turbulence with wind dependence evidenced in very shallow water. Band III indicates a flattening of the spectrum that is related to distant ship traffic. Band IV contains the region best described by the Knudsen spectra with a slope of -5 to -6 dB/octave. Noise originates at the sea surface in the immediate region of the observation. Band V levels are controlled by the thermal noise generated by molecular agitation within the sea. Wenz also divides the spectrum into regions but his classification allows for greater overlap; especially in the region between 10 and 1,000 Hz where turbulence, wind action, and ship traffic interact to modify the noise level.

The shape of the spectrum curves show little time variation. However, the levels present at any location at different times may vary within wide limits. Urick reported a residual variability of from 5 to 10 dB from the average which he attributed to transient sound sources such as marine life or short term changes in the sound transmission conditions. Levels observed in deep water show a consistently higher value in winter than in summer. This variation can be as great as 7 dB and is attributed to better sound transmission during the winter season.

Shallow-water noise levels are generally 5 dB higher than corresponding deep water levels in the frequency range that normally shows wind dependence [Ref. 2]. Piggott's study of ambient sea noise in the shallow waters of the

Scotian Shelf [Ref. 4] showed a seasonal variation between January-April and May-December of 3.5 dB. This variation was found to be frequency independent. Piggott concluded that over the frequency range of 10 to 3,000 Hz, sea noise spectrum levels increase linearly with the logarithm of the wind speed. The rate of increase is frequency dependent although the relative spectral energy distribution of sea noise depends only on the wind speed. He also found noise levels at 20 fms to be 2 to 3 dB higher than those at 28 fms and attributed this to a possible decrease in wind-induced pressure fluctuations with depth.

B. AMBIENT NOISE UNDER ICE COVER

The most obvious effect of ice cover on any body of water is to reduce the interaction of the atmosphere with the water surface. Noise measurements conducted by Payne [Refs. 5 and 6] and Macpherson [Ref. 7] in shallow ice-covered waters showed that there was little or no correlation between under-ice noise levels and wind speed. However, Payne [Ref. 6] demonstrated that low level open water spectra exhibit a relative maximum near 300 Hz, a similar maximum was found to occur in low level under-ice spectra. He suggests that low level under-ice spectra include a small contribution of open water noise, possibly due to incomplete ice cover or propagation from a distant open water source. Payne [Ref. 5] found the lowest open water noise level at 100 Hz to be -50 dB, while at 100 Hz the lowest under-ice level was -70 dB.

High noise levels did occur, however, associated with ice movement. Macpherson [Ref. 7] showed a progressive reduction in under-ice noise levels from January to April, which correlated with consolidation and growth of the ice pack.

Noise measurements were conducted by Milne and Ganton [Ref. 8] in deep water under Arctic sea ice during spring, summer and winter seasons. Winter measurements under shore fast ice, composed of 95 per cent multi-year with five per cent one-year ice, showed that there were distinct quiet and noisy periods corresponding to the times of maximum heating and cooling. Higher noise levels were associated with cooling at lower temperatures. The noise appeared to vary between booms and crashes together with reverberations. Milne and Ganton proposed that tensile stress during cooling caused the cracking noise. Uniform spectrum levels between 20 Hz and 8 kHz were observed on several occasions. This phenomenon was attributed to frequency-independent sound transmissions from impulsive sources.

Summer measurements were made under almost complete cover of one-year ice (70%) and multi-year ice (25%) with new ice formation in open leads. Aural characteristics closely resembled the sound made by escaping steam, in contrast to the winter booms and crashes. Noise in the frequency band from 200 to 400 Hz showed nearly gaussian distribution, while the band from 3.2 to 6.4 kHz appeared non-gaussian. These findings were a reversal of the winter results. Relative motion within the ice pack caused a 10 dB increase in the general level.

The authors summarized the characteristics of under-ice sea noise as:

(1) Generally impulsive and highly non-gaussian.

(2) Resulting from mechanical activity in the most part. The prime source in winter appears to be surface cracking in response to tensile stress, while in summer, relative motion between floes predominated.

(3) Most spectra were not exceptionally low and were occasionally equivalent to a sea state three level.

Wind blowing over the surface of shore-fast ice has been isolated as a mechanism of noise generation especially when the impulsive thermal noise is at a minimum during periods of increasing ice surface temperature [Ref. 9]. Levels increased with windspeed and spectral shapes showed a pronounced response at a preferred frequency. A theoretical model indicated that the critical factor determining response at high frequencies is snow thickness, while at low frequencies ice thickness is more important.

III. ENVIRONMENTAL CONDITIONS

A. ICE CONDITIONS

1. Reporting System

Ice reports and forecasts were provided by Ice Forecast Central, Halifax, Nova Scotia; these were supplemented by photographs of the local area.

A special ice observing and reporting system has been developed in Canada. This section explains only those features necessary to decode information on the charts illustrated. The basis of the system is that the amount of ice in each of six age categories is reported in invariable order:

Multi-Year ice
Second Year ice
First Year ice
Grey-White ice
Grey ice
Nilas and New ice.

Amounts are reported as tenths coverage by class. The older forms are omitted if they are not present. This means that nilas and new ice always appears in the units column, grey ice in the tens column, etc. The amount of medium floe size or greater is also reported and this appears on the second line of the report immediately below the age class comprising the floe. A medium floe is over 100 meters long. For

example: $\frac{4210}{3\ 1}$ indicates four tenths first year ice of which three tenths is in floes medium size or greater; two tenths grey-white ice is present all less than medium floe size; one tenth grey ice all medium floe size or greater with no nilas or new ice.

Other reporting features:

(1) A solidus (/) is used to indicate some floes but less than one tenth of any class.

(2) When more than nine but less than ten tenths total ice cover is observed, the concentration by class will total ten and the report will be circled.

(3) To distinguish between one tenth of an age class and ten tenths of the next lowest, a change in digit size is mandatory; thus 100 indicates one tenth of grey-white ice while 10o indicates ten tenths of grey ice.

(4) Additional symbols are included in Table 1.

2. Cape North Ice Conditions

a. General

The Ice Forecasting Service, Canada Department of Transport, conducted a ten-year survey of ice conditions in the Cape North area between 1957 and 1966. It was found that first onset of ice occurred in early January and that the latest time ice persisted was mid-May. Average conditions indicate an ice season extending from late January to early April. No ice was present in the Cape North area during 1958.

The presence of consolidated pack ice in the vicinity of Cape North is a function of the severity of the

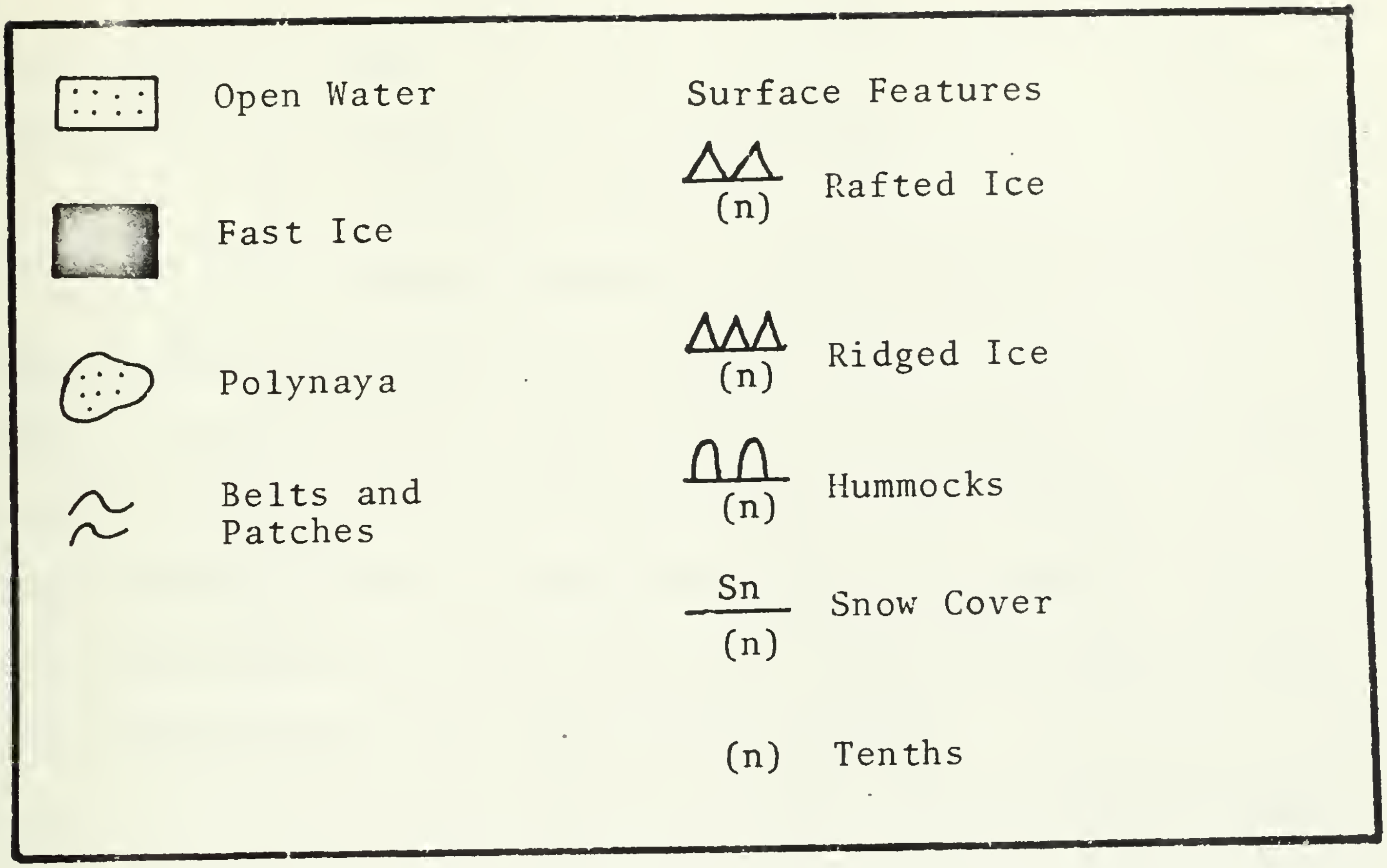


Table I. Additional symbols for ice reporting.

winter and the wind direction. A moderately cold winter with persistent north to northwest winds can produce a broad area of heavy ice to the north and west; however, a shift in wind direction to south or southeast results in large leads opening along the coast. During periods when heavy ice is drifting through the Cabot Strait, a shift to east or northeast winds will compact ice on the shore in Bay St. Lawrence and along the shore south of Cape North. Mild temperatures result in rapid melting of any ice compacted along the shore. The ice near Cape North never attains shore fast status.

The survey stated that in an average year, ice thickness ranges from two to four feet but may attain five to six feet during very cold winters.

b. Ice Season 1970-71

Ice was present in the vicinity of Cape North from 22 January until 11 April 1971. Southeasterly winds caused the ice to move offshore on several occasions, notably 12 February and 20 to 22 March. The greatest ice concentration, both at Cape North and in the central Gulf, occurred between 20 and 22 February, while the heaviest ice was present during the first week of March.

Summaries of ice conditions present at Cape North during analysed runs follow:

(1) 29 January 1971: The Ice Central codes 1342 and 4/6 show active development and progression to more mature forms (Figure 3). Figures 4 and 5 place the main pack 11/2 miles to seaward of Cape North while the bay is partially filled with nilas. Figure 5 indicates westward movement along the inshore edge of the pack. This is a response to currents since the wind was 5 mph from the southwest.

(2) 22 February 1971: The Ice Central code $\frac{5311}{41}$ shows the ice to be almost at its maximum maturity for the season. The presence of five tenths medium size floes indicates a greater stability within the ice field than in the previous report (Figure 6). Figures 7 and 8 show the development of a large lead at the mouth of the bay. This

was in response to tidal currents and occurred over a three-hour period. Figure 8a shows the effect of the tidal oscillation along the shoreline and indicates a series of cracks extending from the shore. Figures 9 and 10 show ridging along the edges of the floes and the large amount of brash near the refrozen lead in the left center of Figure 9 indicates that there has been considerable shear within the pack. Wind during this sequence was 10 mph from the northwest.

(3) 1 March 1971: The Ice Central codes indicate transition from $\frac{4220}{42}$ to 5111 in the vicinity of Cape North (Figure 11). Figure 12 shows that the bay was filled with numerous broken and rafted floes; this indicates that the large first-year ice floes have broken up in response to a recent storm.

(4) 5 March 1971: The Ice Central codes indicate a junction between $\frac{6400}{1}$, 5311 and open water at Cape North. A tape commentary for 6 March recorded ice extending seaward 11/2 miles with open water beyond. The wind was 25 mph from the west.

(5) 15 March 1971: The Ice Central Code 2221 indicated that some of the first-year ice had melted and that some grey and new ice had formed. Tape commentary reported the bay was clear except for scattered floes and that the main pack was 11/4 miles offshore.

(6) 16 April 1971: No ice was present in the vicinity.

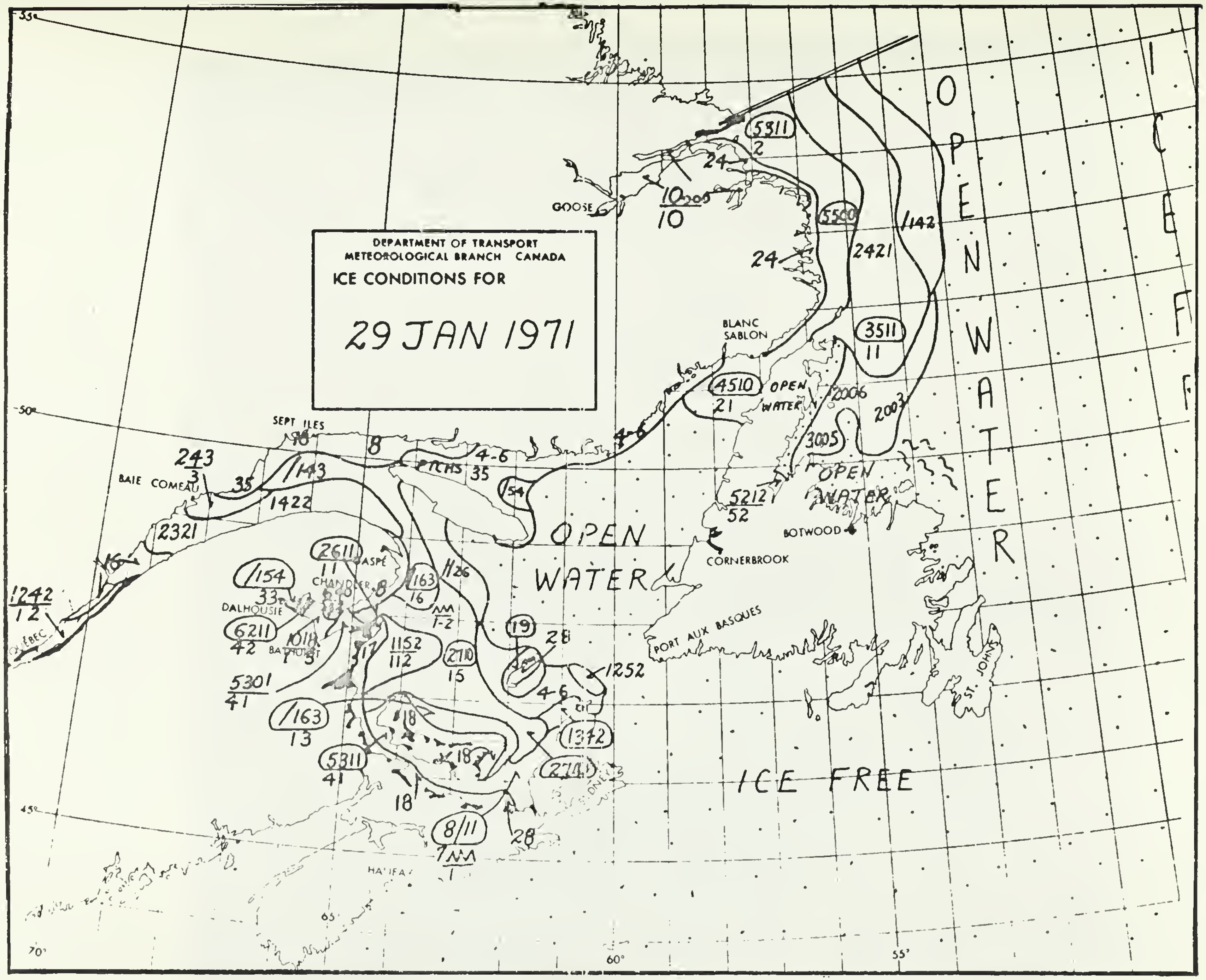


Figure 3. Eastern Region ice conditions, 29 January 1971.

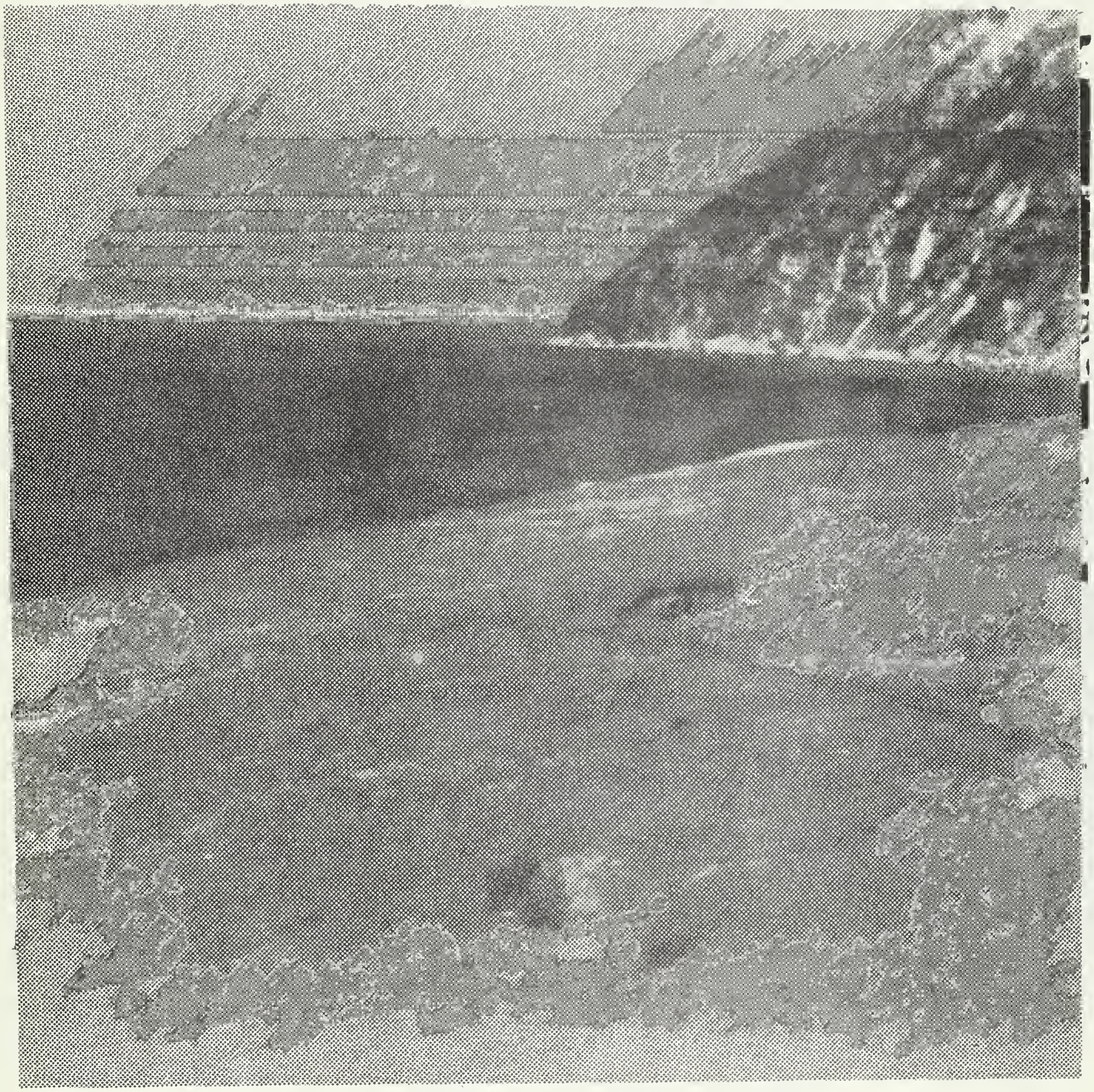


Figure 4. Cape North, 29 January 1971.
Ice field to seaward of the Cape,
formation of new ice in the bay.

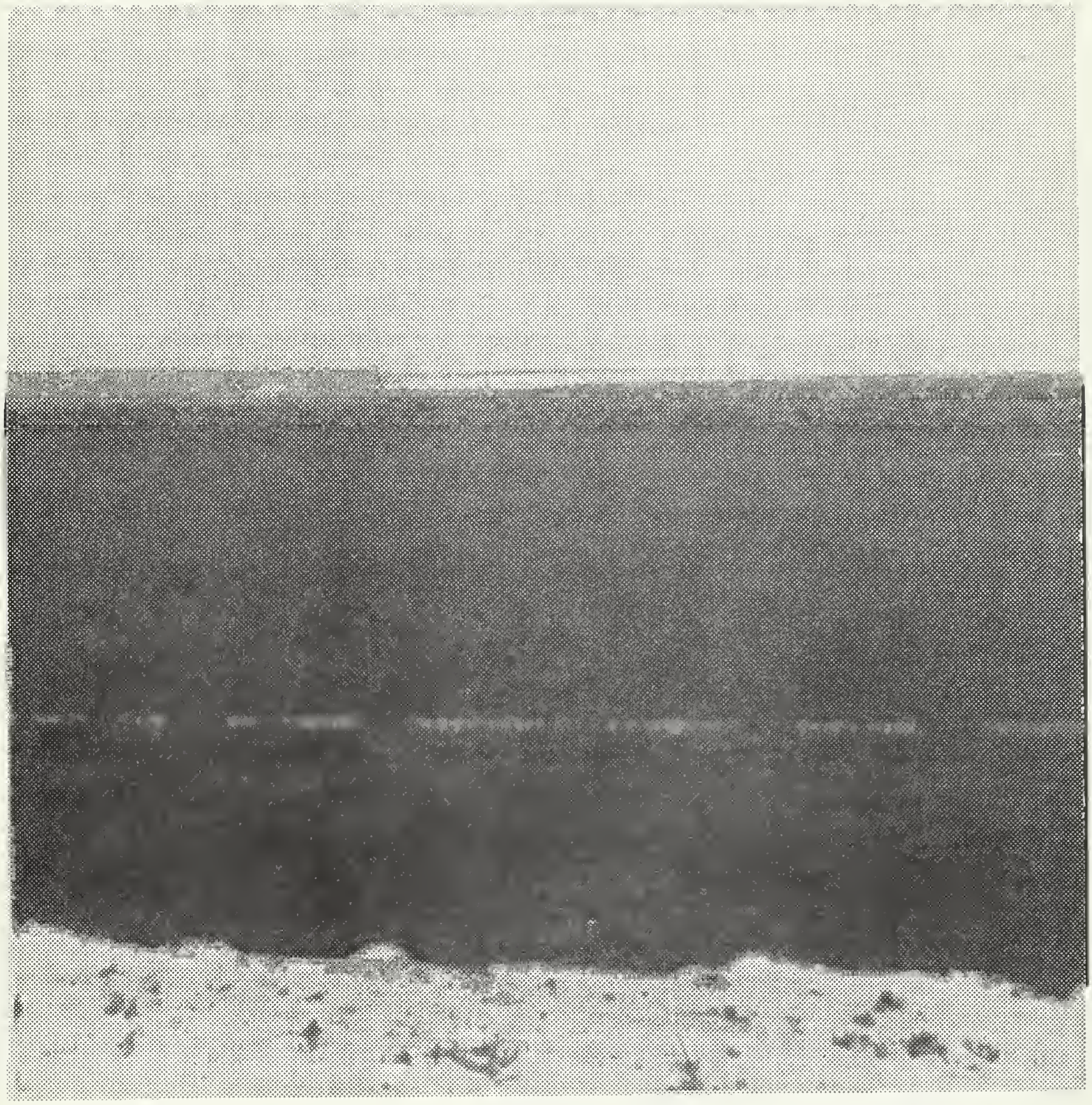


Figure 5. Bay St. Lawrence, 29 January 1971, showing movement along inshore edge of ice pack.

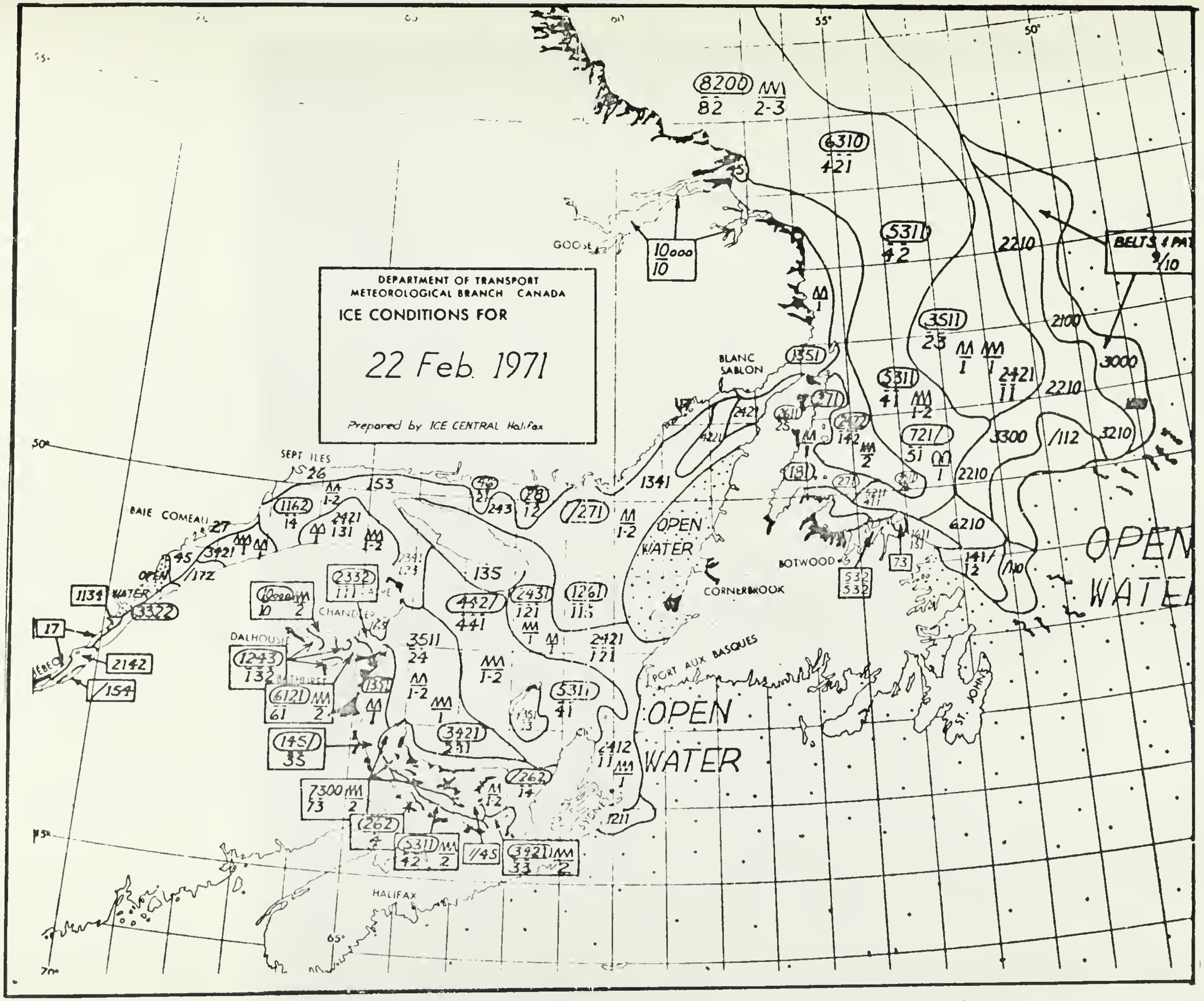
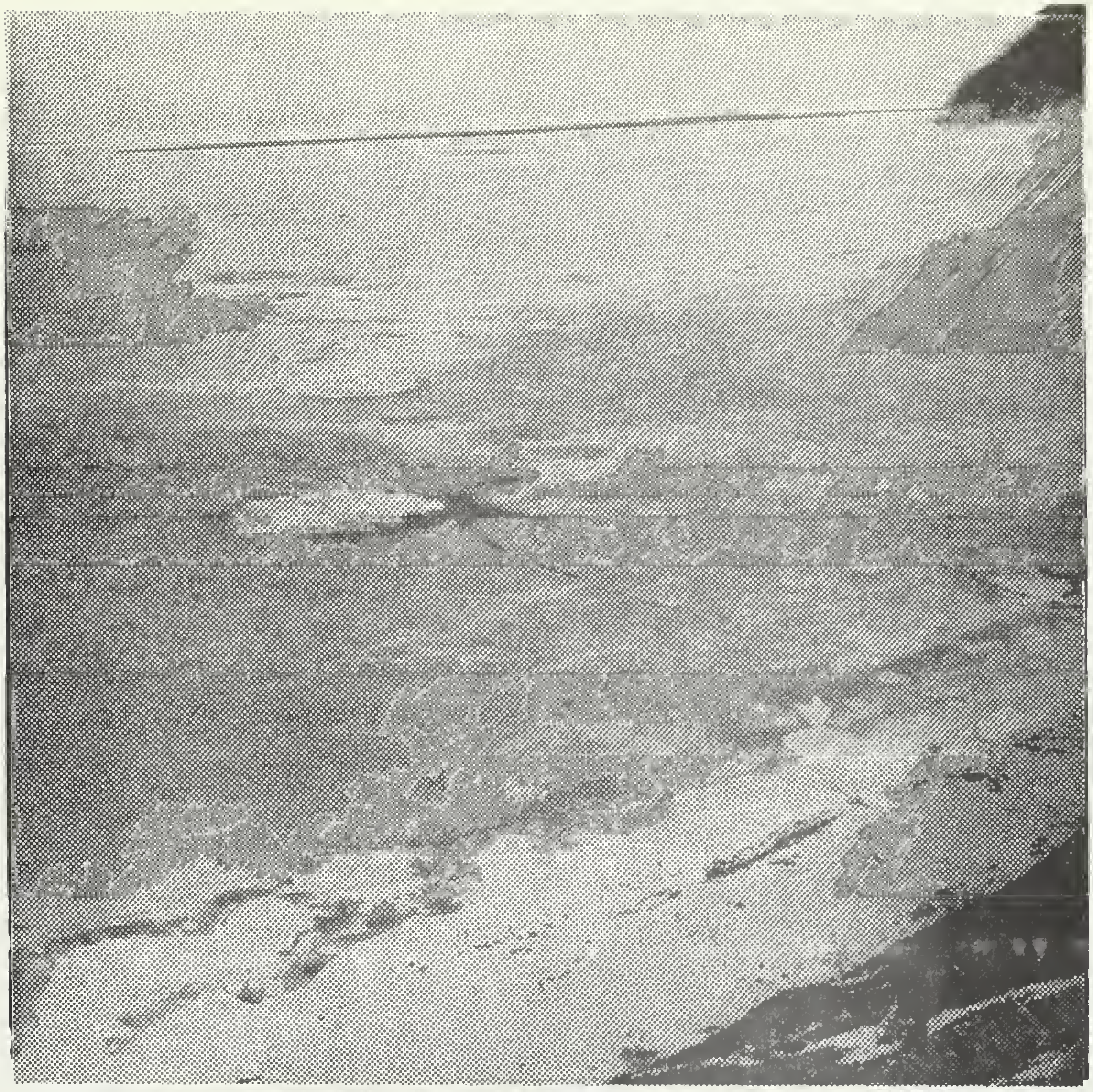


Figure 6. Eastern Region ice conditions, 22 February 1971.

Figure 7. Cape North, 1100 22 February 1971.
The dark patch left center
is a refrozen lead.



(a)

(b)

Figure 8. Cape North, 1230 22 February 1971. Note obvious movement of ice at mouth of Bay St. Lawrence.

Figure 9. Bay St. Lawrence, 22 February 1971, showing ridging along floe edges, and large amount of brash near refrozen lead left center.

Figure 10. Black Point, 22 February 1971.
Open lead extends from Black Point
to Cape North.

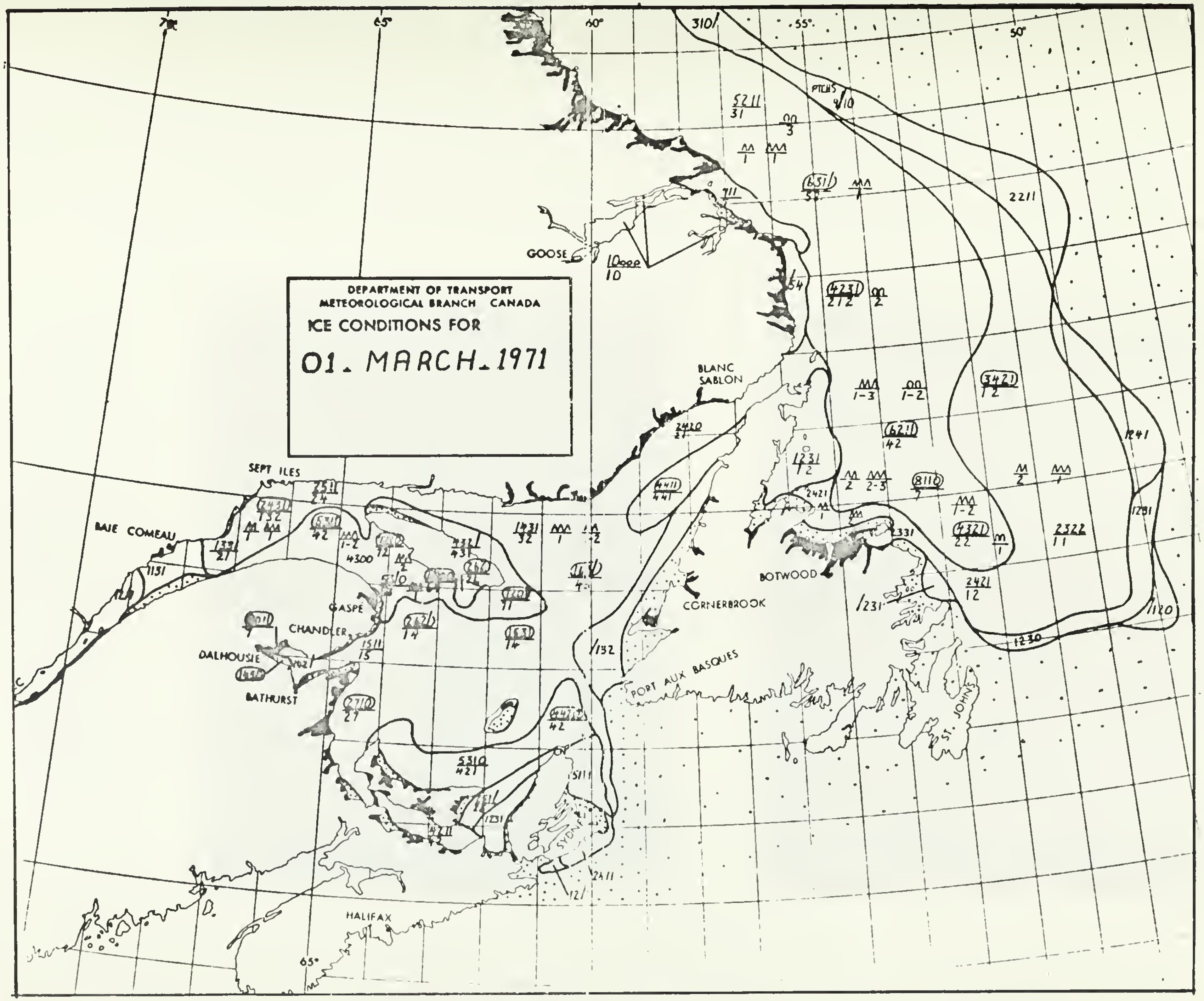
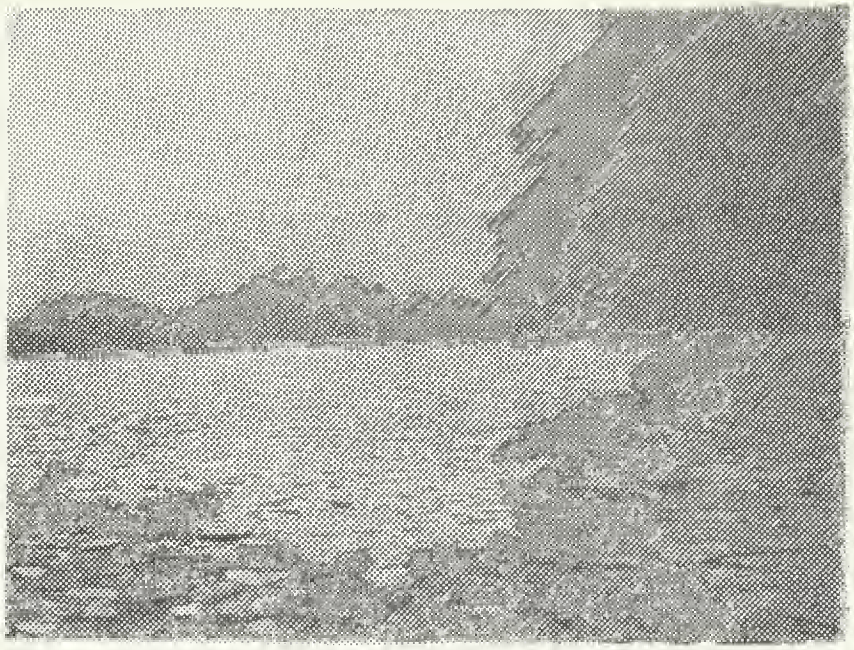
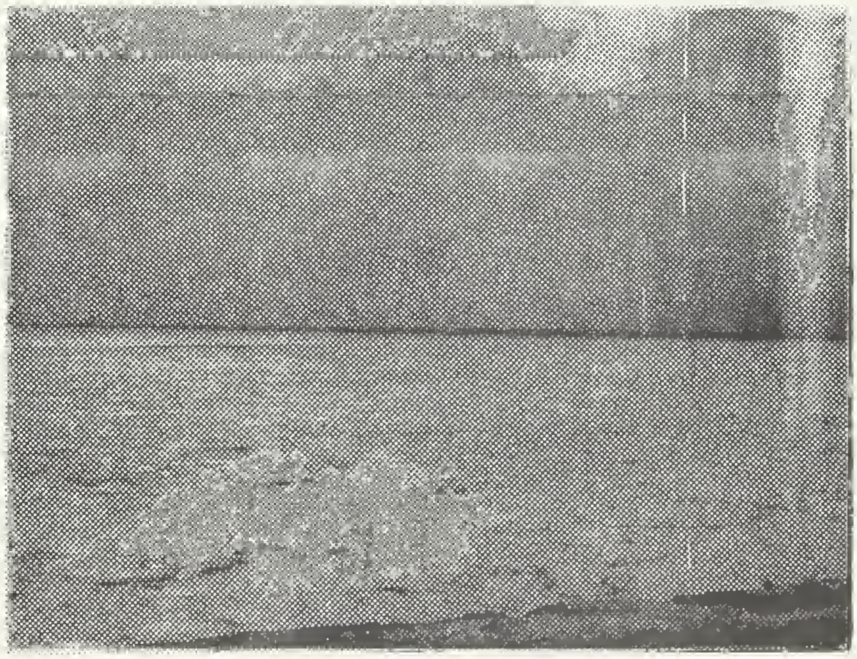


Figure 11. Eastern Region ice conditions, 1 March 1971.



(a)



(b)

Figure 12. Ice conditions in Bay St. Lawrence, 2 March, 1971. Broken and rafted ice caused by recent storm.

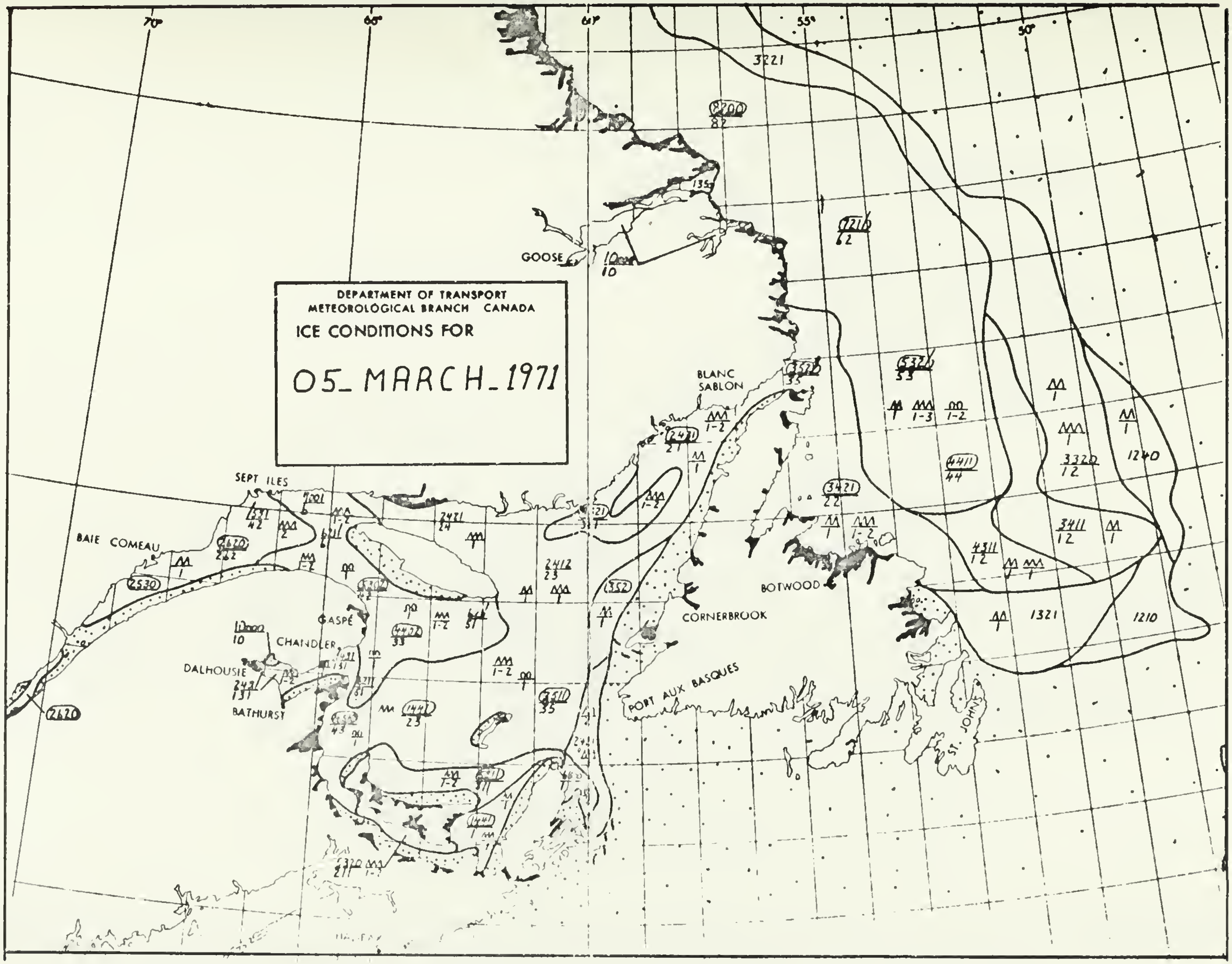


Figure 13. Eastern Region ice conditions, 5 March 1971.

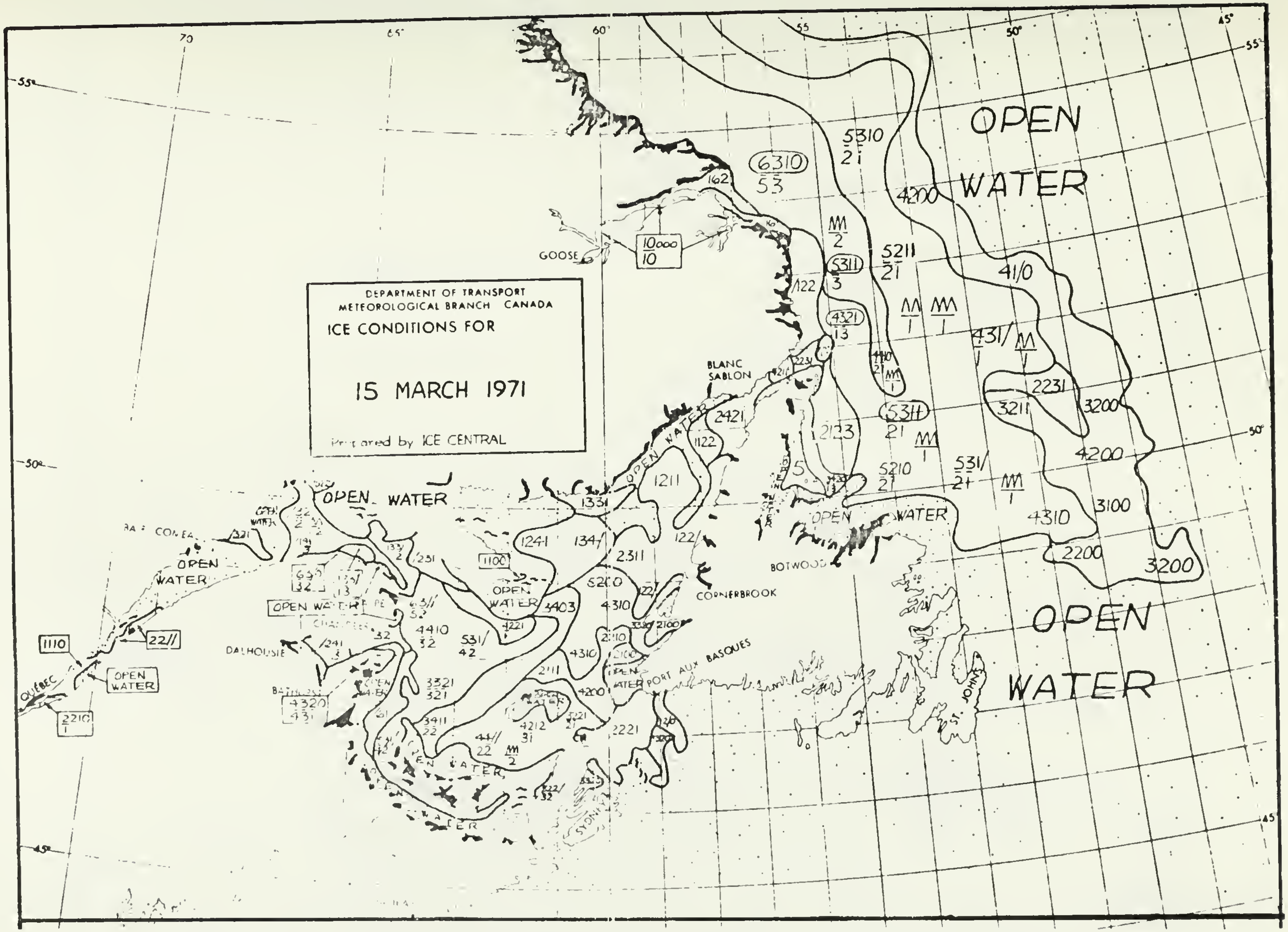


Figure 14. Eastern Region ice conditions, 15 March 1971.

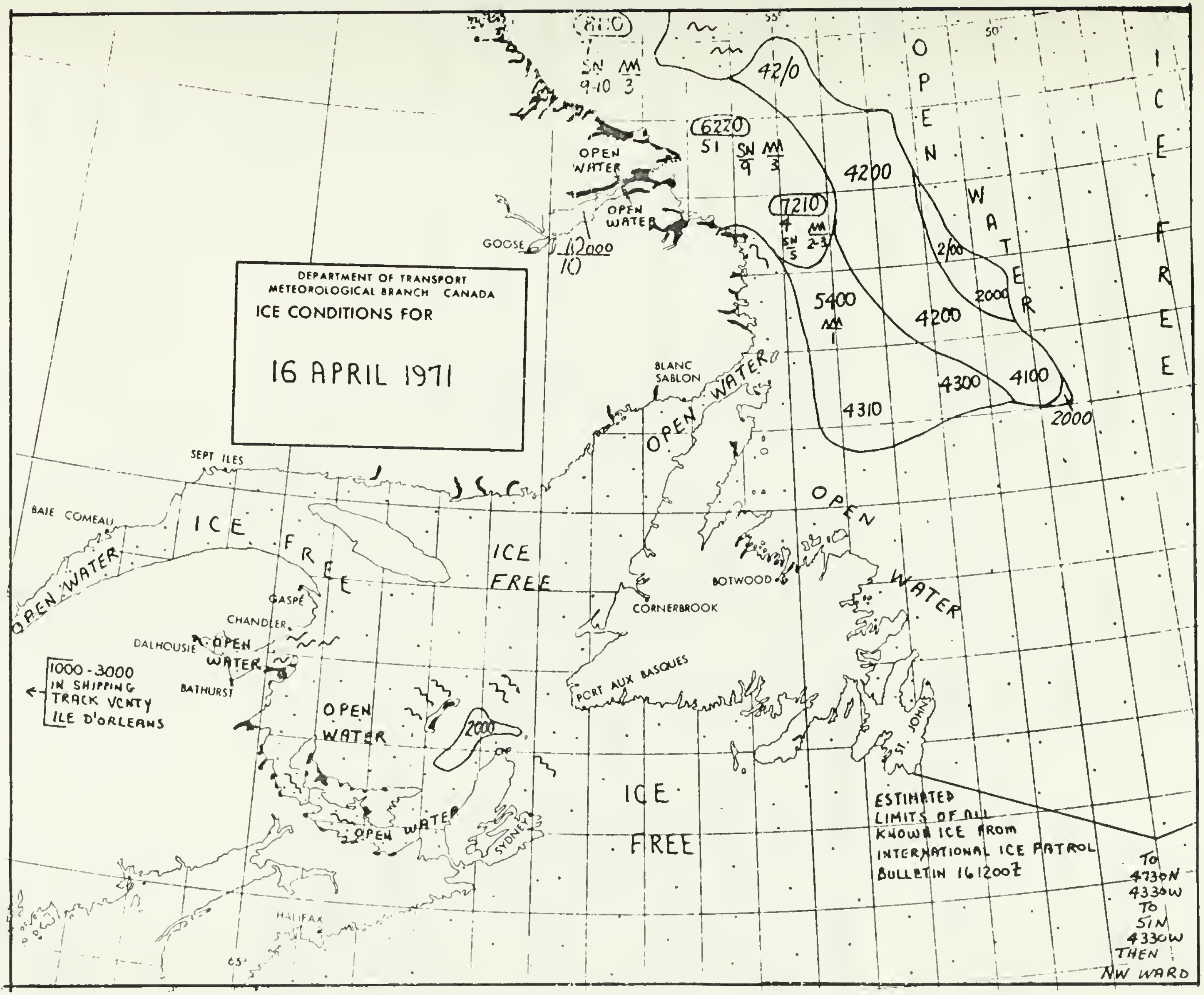


Figure 15. Eastern Region ice conditions, 16 April 1971.

B. TEMPERATURE AND SALINITY

The ocean near Cape North exhibits a distinctive three-layer structure in temperature and salinity.

1. A warm surface layer with temperature ranging from 30°F during the winter to 70°F in late summer. Salinity varies from 26 o/oo in spring to 32 o/oo in late fall. Its vertical extent varies from 60 feet in summer to 170 feet during the winter.

2. A cold intermediate layer with a temperature range from 30 to 35°F; the salinity varies from 32 to 34 o/oo with the decrease occurring in late summer. This indicates that the thermocline develops sufficiently rapidly in the spring to prevent the efflux of fresh water from mixing during spring runoff. The fresh water itself will aid the stratification. Thickness ranges from less than 100 feet in summer to 200 feet in the winter.

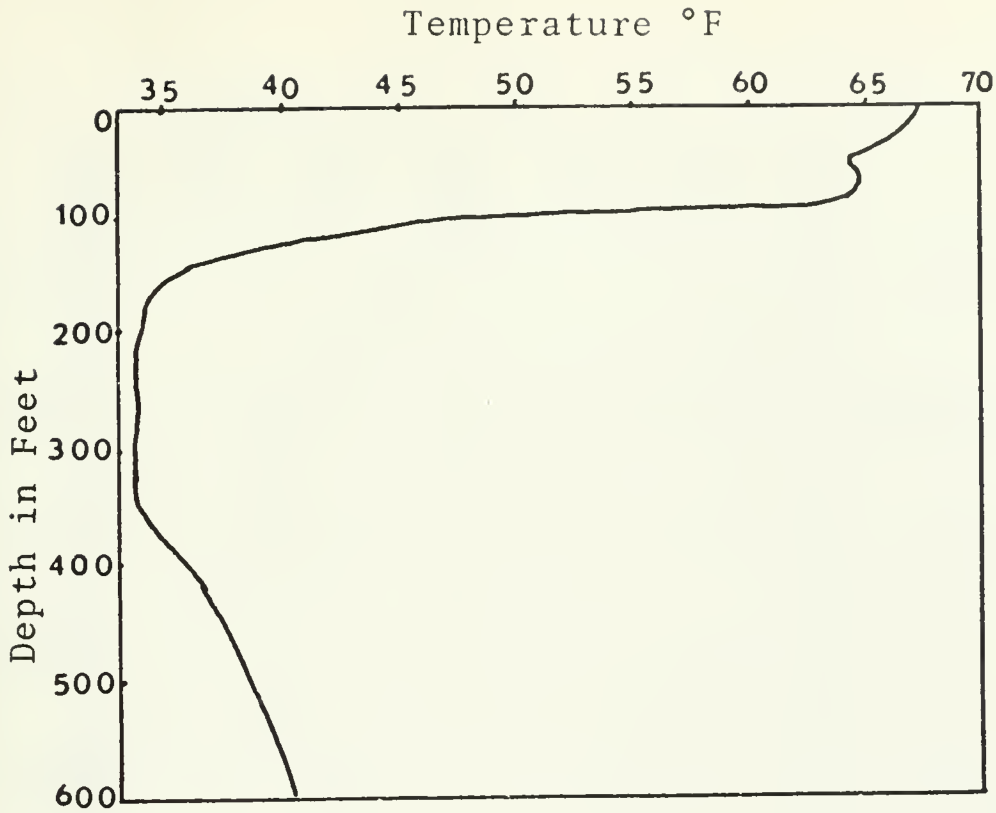
3. A deep warm layer with a temperature near 40°F and a salinity in excess of 34 o/oo is the result of Labrador current and slope water flowing into the Gulf of St. Lawrence [Ref. 11].

The surface layer is produced by water from the St. Lawrence River flowing out of the Gulf of St. Lawrence through the Cabot Strait. Progressive cooling of the surface throughout the fall, coupled with the maximum in surface salinity, overcomes the density stratification. Thus convective and wind mixing extend to greater depths. Extreme winter cooling, followed by the development of strong

temperature and salinity gradients in the spring, re-establish the density stratification and produce the intermediate cold layer.

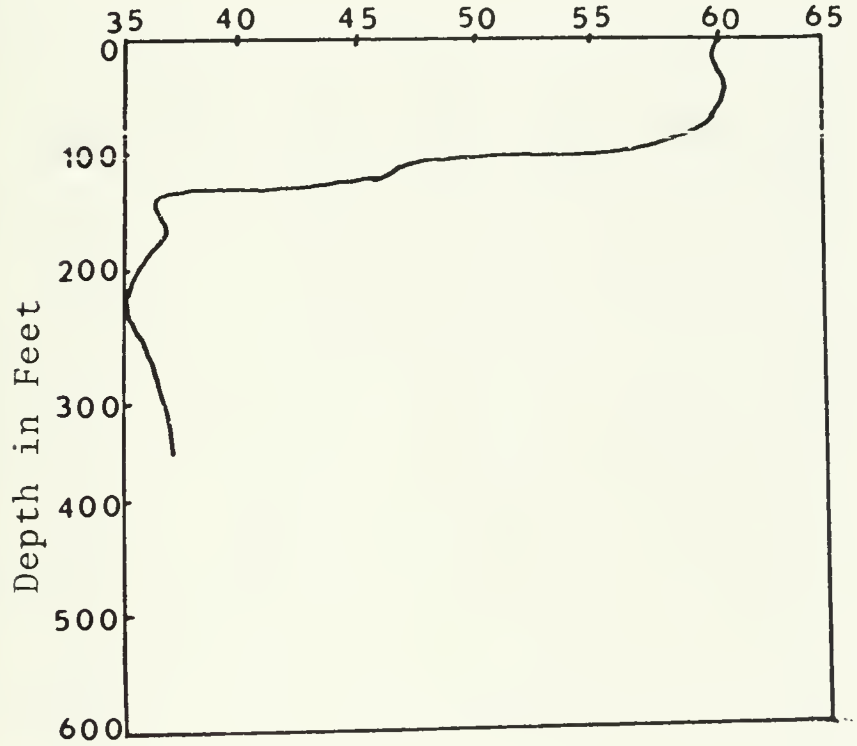
Figures 16 to 18 depict seasonal variations in the three-layer temperature profile. The August profile shows that the surface and intermediate layers are at their minimum thicknesses and they are separated by a very strong negative gradient. Transition between the intermediate and deep layers is through a moderate positive gradient (Figure 16a). Surface cooling becomes effective in September (Figure 16b) and becomes progressively stronger so that by November the surface layer has deepened to 170 feet and shows a layered structure of its own. The maximum of surface salinity, late fall storms and continued cooling combine to produce a deep well-mixed surface layer that has merged with the upper part of the intermediate layer by December (Figure 17). The January and February profiles are typical of mid-latitude winter conditions. The surface and intermediate layers are essentially at the same temperatures and merge with the deep layer through a slight positive gradient (Figure 18). Figure 19 indicates the transition from a strong summer thermal stratification to a more uniform winter condition.

The intermediate layer forms a well defined sound channel during the summer; thus distant sound sources will make a greater relative contribution to the spectrum received by a hydrophone in the layer than locally generated surface



(a)

August



(b)

September

Figure 16. Typical Cape North temperature profiles, August and September.

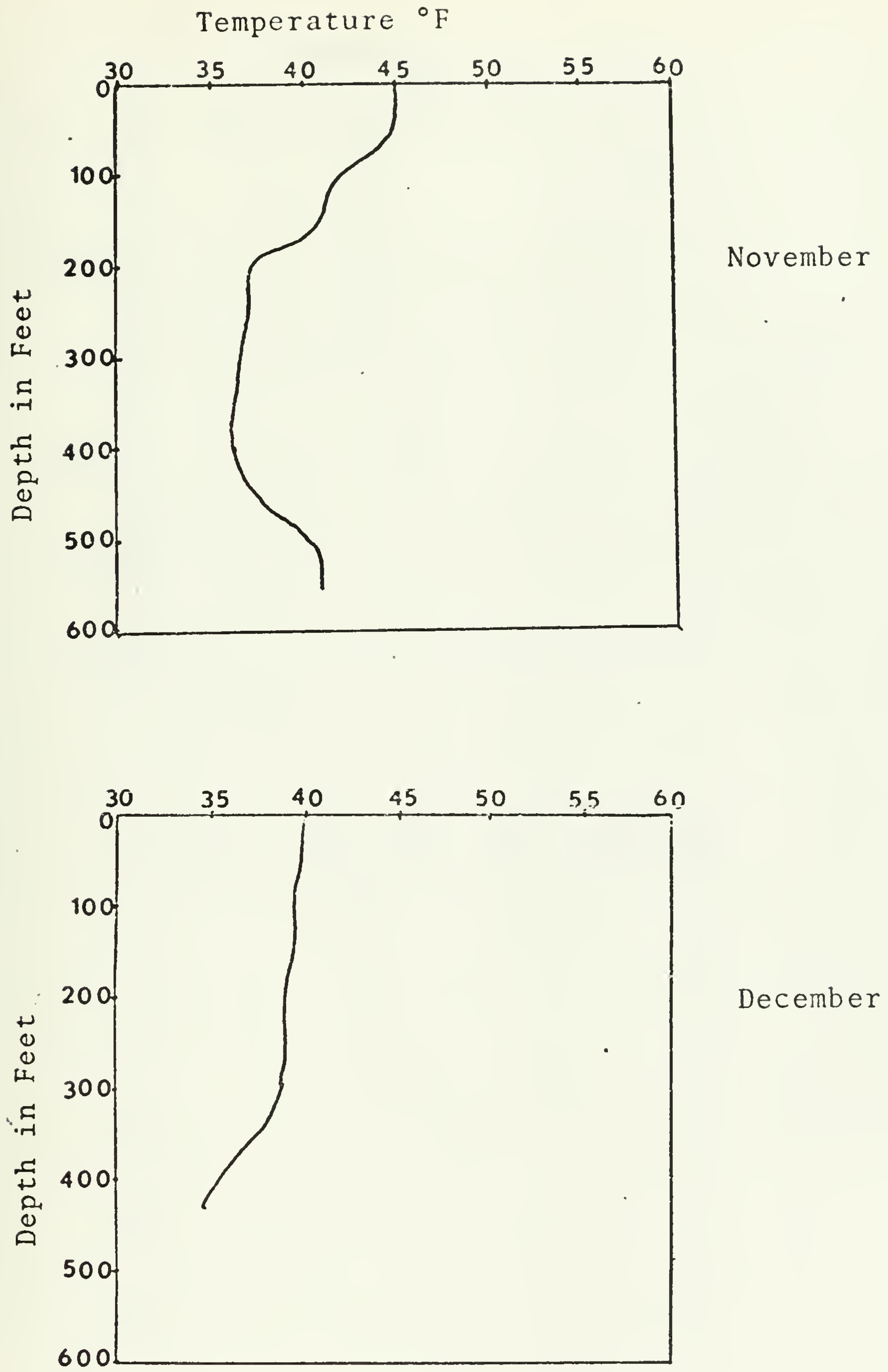
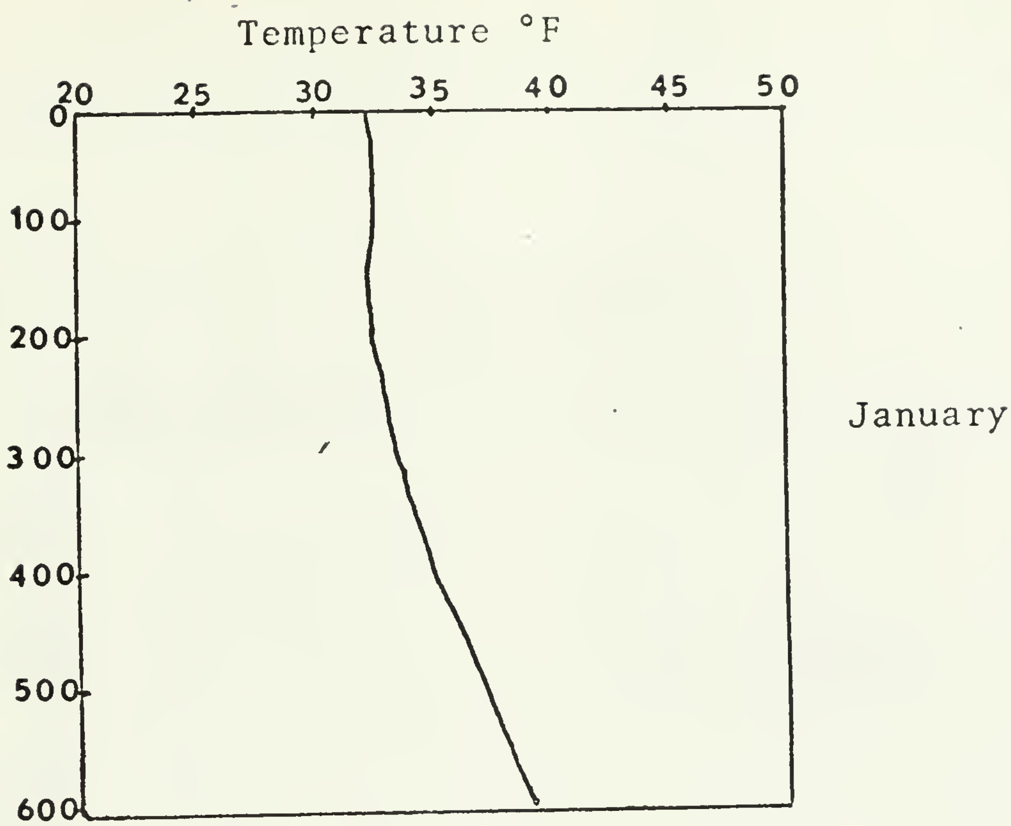


Figure 17. Typical Cape North Temperature Profiles, November and December



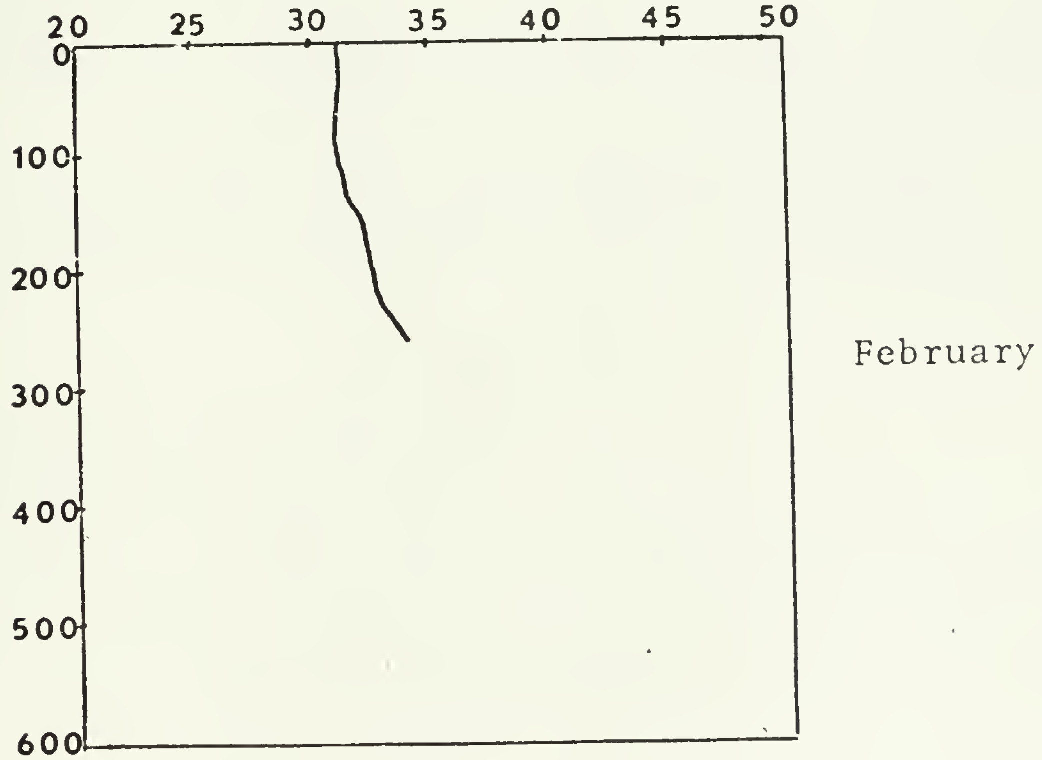


Figure 18. Typical Winter Temperature Profiles, Cape North.

noise. More uniform winter sound transmission conditions will shift the balance in favor of local surface sources.

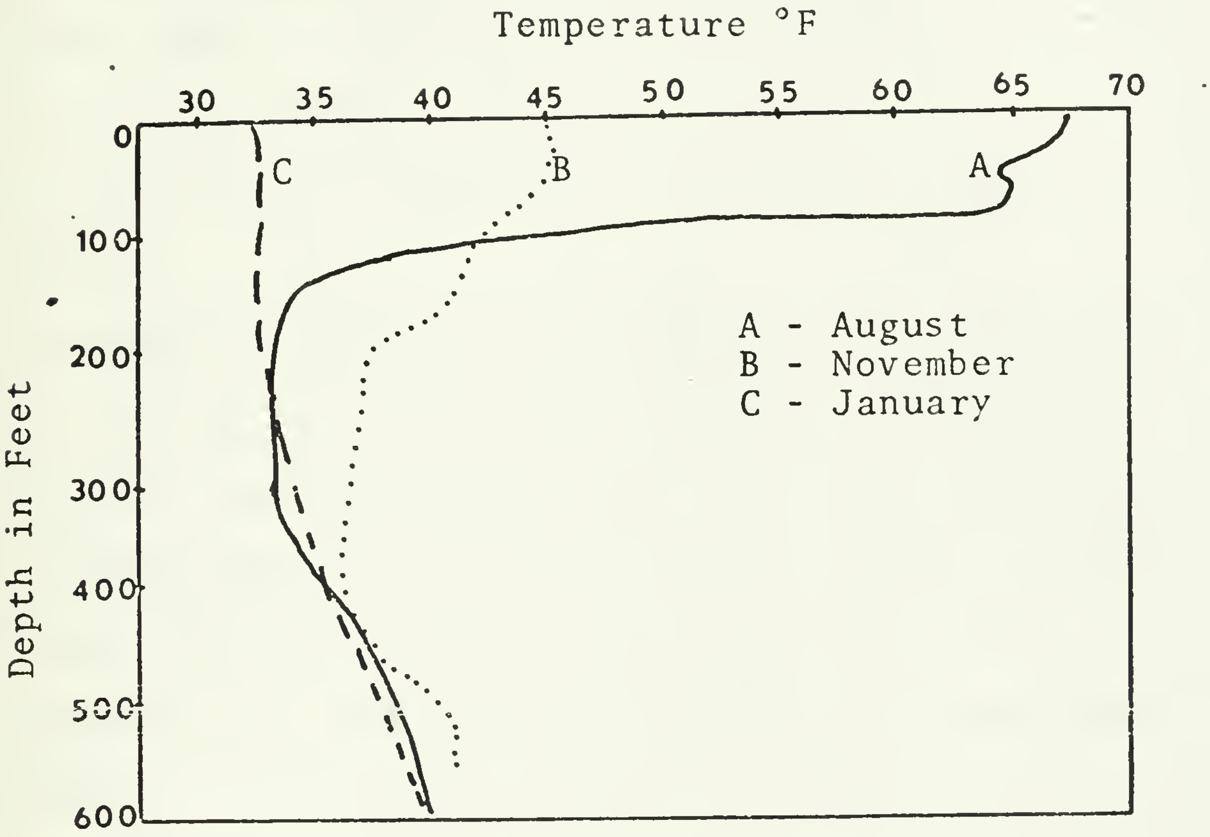


Figure 19. Temperature profiles showing transition from summer to winter conditions.

C. TOPOGRAPHIC FEATURES[1]

Ice margins during periods of glaciation almost always extended from the coast across the continental shelf. The principal topographic features of such a shelf are irregular

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[1] Information in this section was provided by Naval Ordnance Laboratory from original survey data.

terrain with many deep basins and troughs [Ref. 11]. The continental shelf surrounding Cape North is classified as a glaciated continental shelf.

The hilly mountainous terrain of the Cape North area continues onto the continental shelf and is terminated by the Laurentian Channel that runs southeast through the Cabot Strait (Figure 20). Depths in this channel range from 200 to 250 fms.

The underwater acoustic arrays have been placed at a depth of 65 fms in an area where there is a relatively gentle slope seaward (Figure 21). The cables run along a very steep trough from the 60 to 10 fm contour. In the surf zone, they are protected in a covered trenth.

Core and grab samples indicate that the region consists of a jagged, firm rock bottom near shore and in the trough. The area surrounding the arrays consists primarily of small rocky patches interspersed with areas of sand and mud. There is little evidence of thick sedimentary deposits.

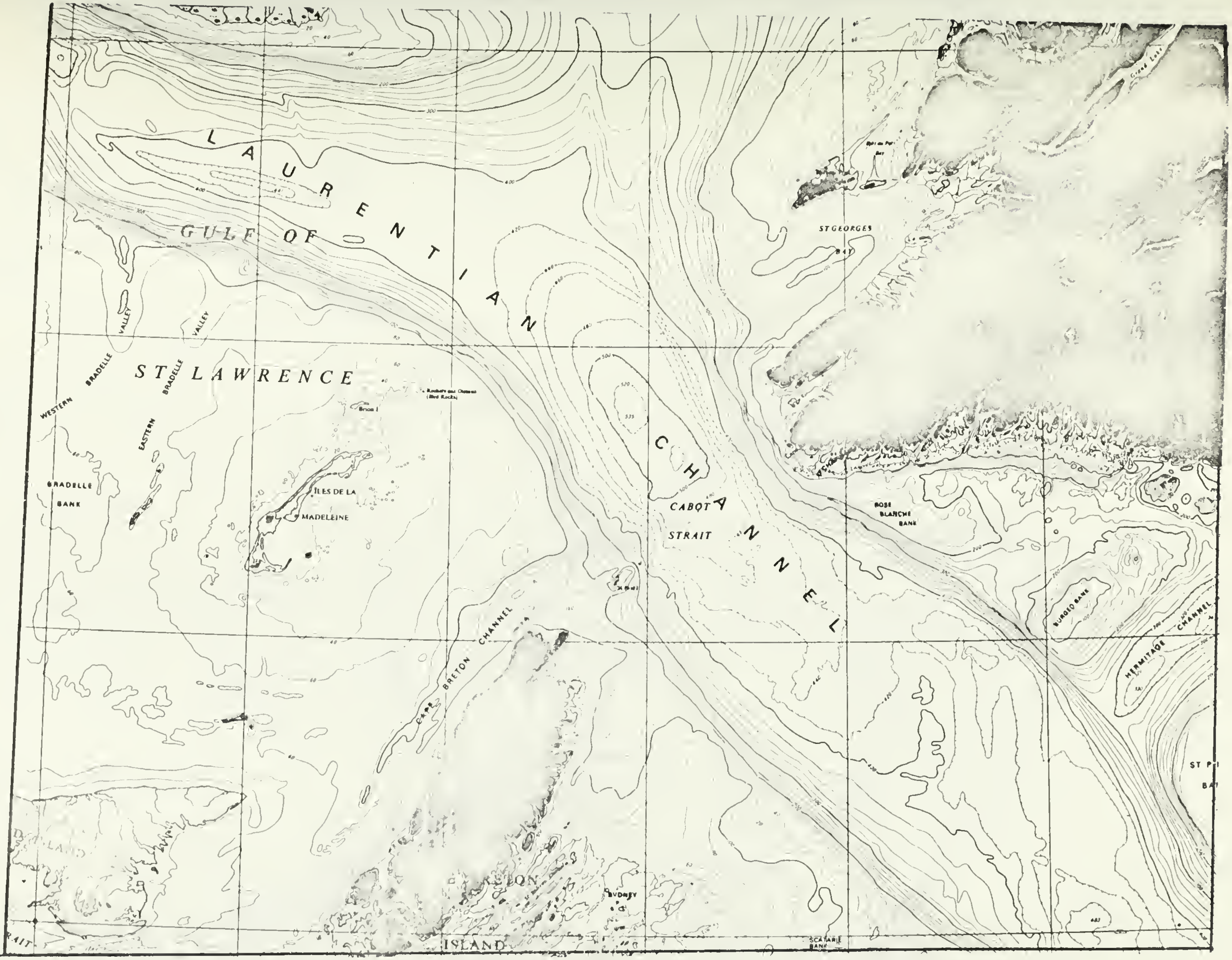

Figure 20. Bathymetric features of the Cabot Strait entrance to the Gulf of St. Lawrence. From Canadian Hydrographic Service Chart 801.

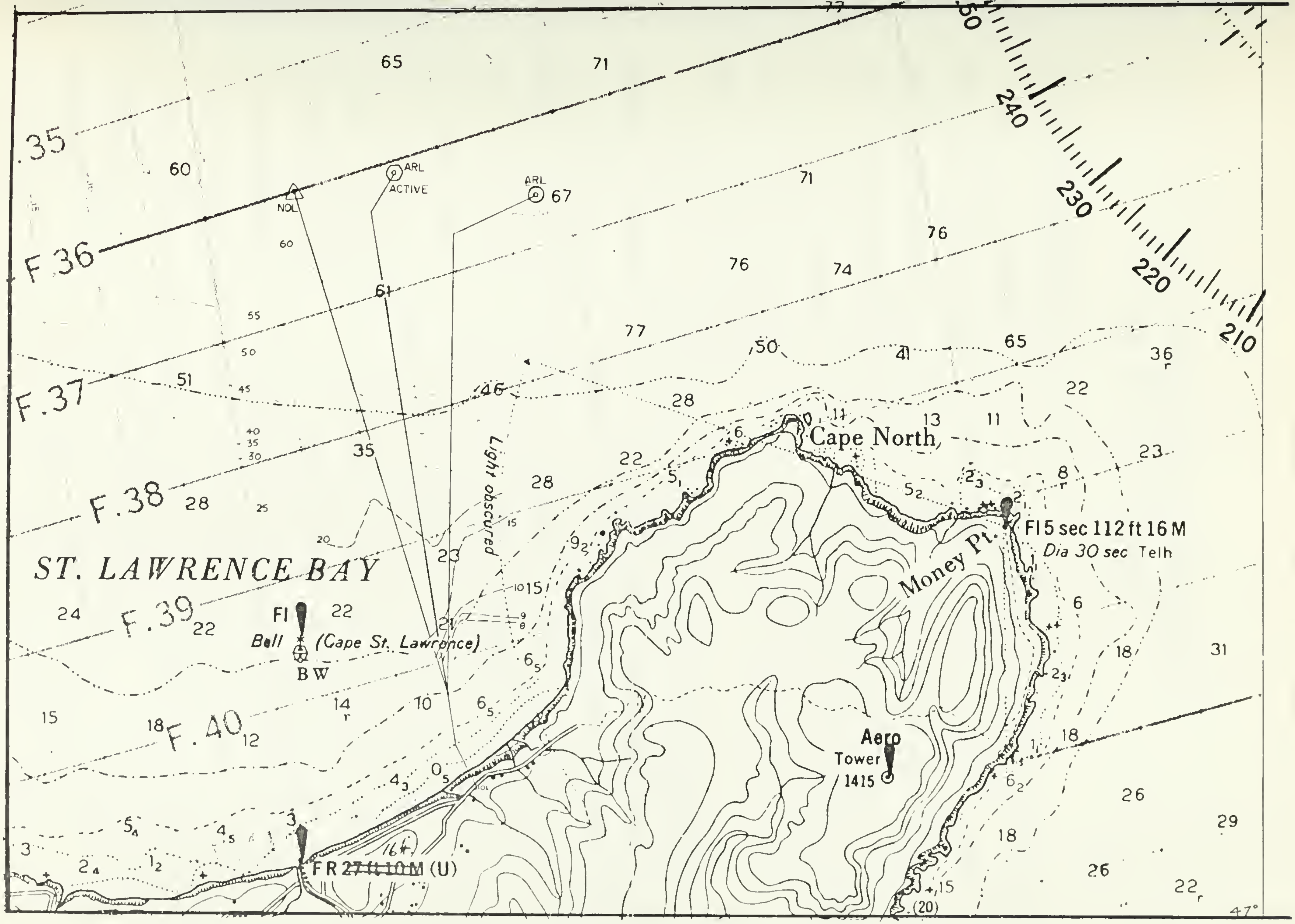

Figure 21. Bay St. Lawrence, showing location of NOL and ARL arrays.

IV. DESCRIPTION OF RECORDING AND ANALYSIS EQUIPMENT

A. NOL INSTRUMENTATION PACKAGE

The instrumentation package consists of three information channels; two identical low-frequency, 20 Hz to 10 kHz, and one high-frequency, 20 Hz to 60 kHz. The three hydrophone pre-amplifier combinations are supported in a vertical line by a platform placed on the seafloor (Figure 1). The top and bottom hydrophones are low-frequency while the center hydrophone is high-frequency.

Figure 22, a functional block diagram of the instrument package, is intended to be used in conjunction with the following description. The low-frequency hydrophone pre-amplifier outputs are fed directly to ganged six-stage variable gain amplifiers, while the high-frequency pre-amplifier is fed through a four-position band pass filter before being applied to a separate variable gain amplifier. Control for the filter and amplifiers is provided by three six-pole, six-position switches. These switches are stepped by means of tones generated by tone generators at the shore end of the cable. The presence of a tone on the cable is detected by a tone discriminator in the underwater package which applies a signal to activate the appropriate switch. Switch A, the filter switch, is actuated by a 14.5 kHz tone; a 7.35 kHz tone steps switch B, the high-frequency amplifier; while a

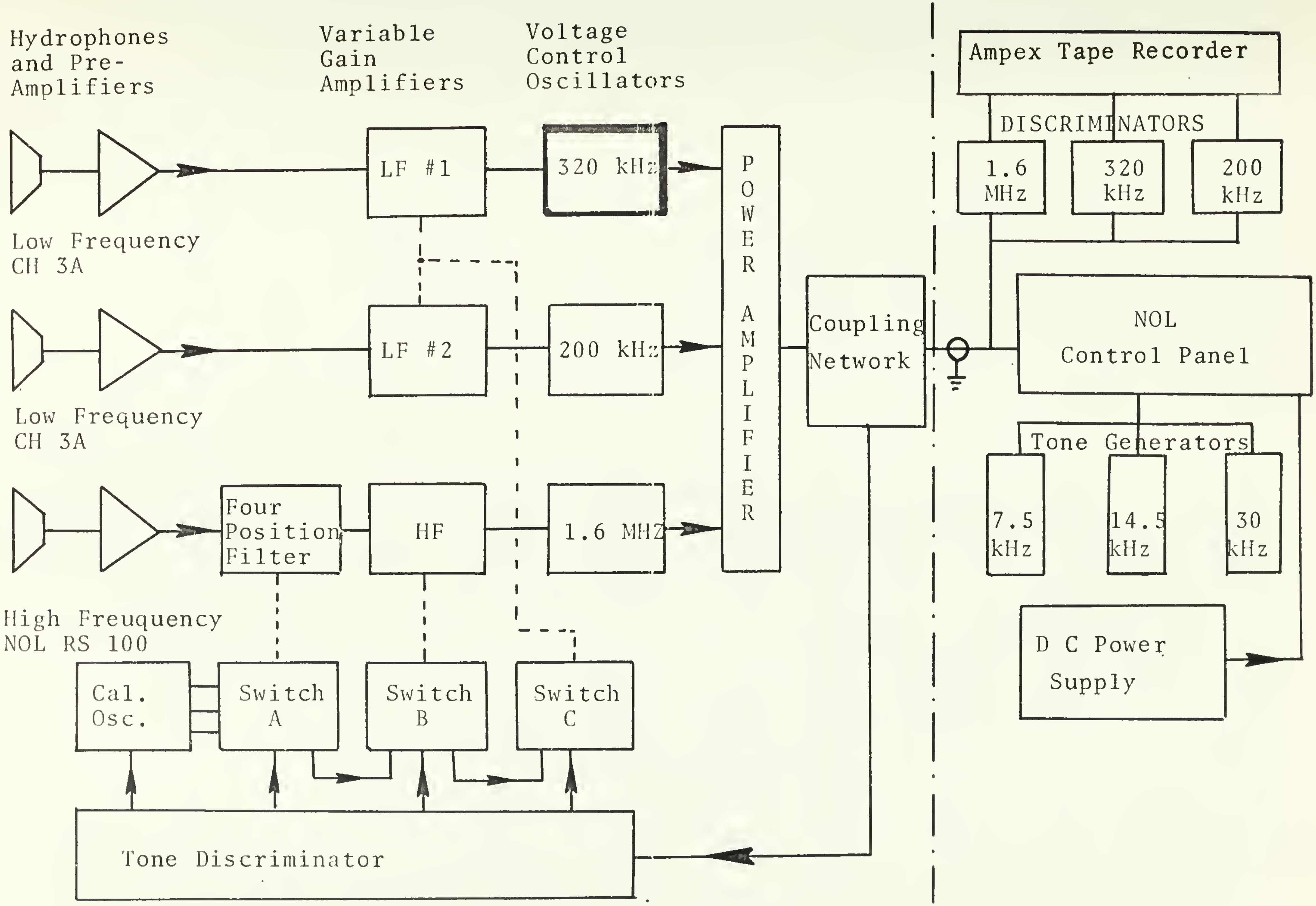

Figure 22. NOL instrumentation package.

Position	Switch A HF Filter Switch	Switch B HF Gain	Switch C LF Gain Top	Bottom
1	30 Hz to 60 kHz	6 dB	0 dB	0 dB
2	30 Hz to 7 kHz	0 dB	0 dB	0 dB
3	30 kHz to 60 kHz	12 dB	12 dB	12.3 dB
4	10 kHz to 30 kHz	20 dB	20 dB	20 dB
5	30 Hz to 60 kHz	29.4 dB	32 dB	32.5 dB
6	A6 and B1 short input to three pre-amps for self-noise test.	40 dB	39.5 dB	39.3 dB

Table II. Switch Position Functions.

30 kHz tone steps switch C, the low-frequency amplifier. Table 2 details the various functions of each switch position.

When the NOL control panel switches are in positions A1, B1, and C1, a calibration oscillator is activated by the tone discriminator and a 4 kHz signal should be monitored at the output of all three channels. The calibration level input to the tape recorder was set to 1.4 volts peak-to-peak for the low-frequency channels and 2.8 volts peak-to-peak for the high-frequency channel.

The RS 100 hydrophone pre-amplifier voltage receiving response for a low-frequency channel (Figure 23) is flat from 30 to 500 Hz. The maximum deviation throughout the upper response region is ± 2.5 dB. The overall frequency response characteristics of both low frequency channels (Figure 24) shows that except in the ranges 20 to 80 Hz and 8 to 10 kHz, system frequency response corrections are unnecessary.

Voltage receiving response for a Clevite CH-3A hydrophone pre-amplifier combination (Figure 25) indicates uniform sensitivity over a wide frequency range. Frequency-response characteristics with various filter positions (Figures 26 to 29) indicate that in the wide-band position, A 1, positive corrections of up to 5 db are required for frequencies above 22 kHz. Vertical and horizontal response patterns are essentially omnidirectional.

Outputs from the variable gain amplifiers are used to modulate standard frequency modulated channels. Carrier

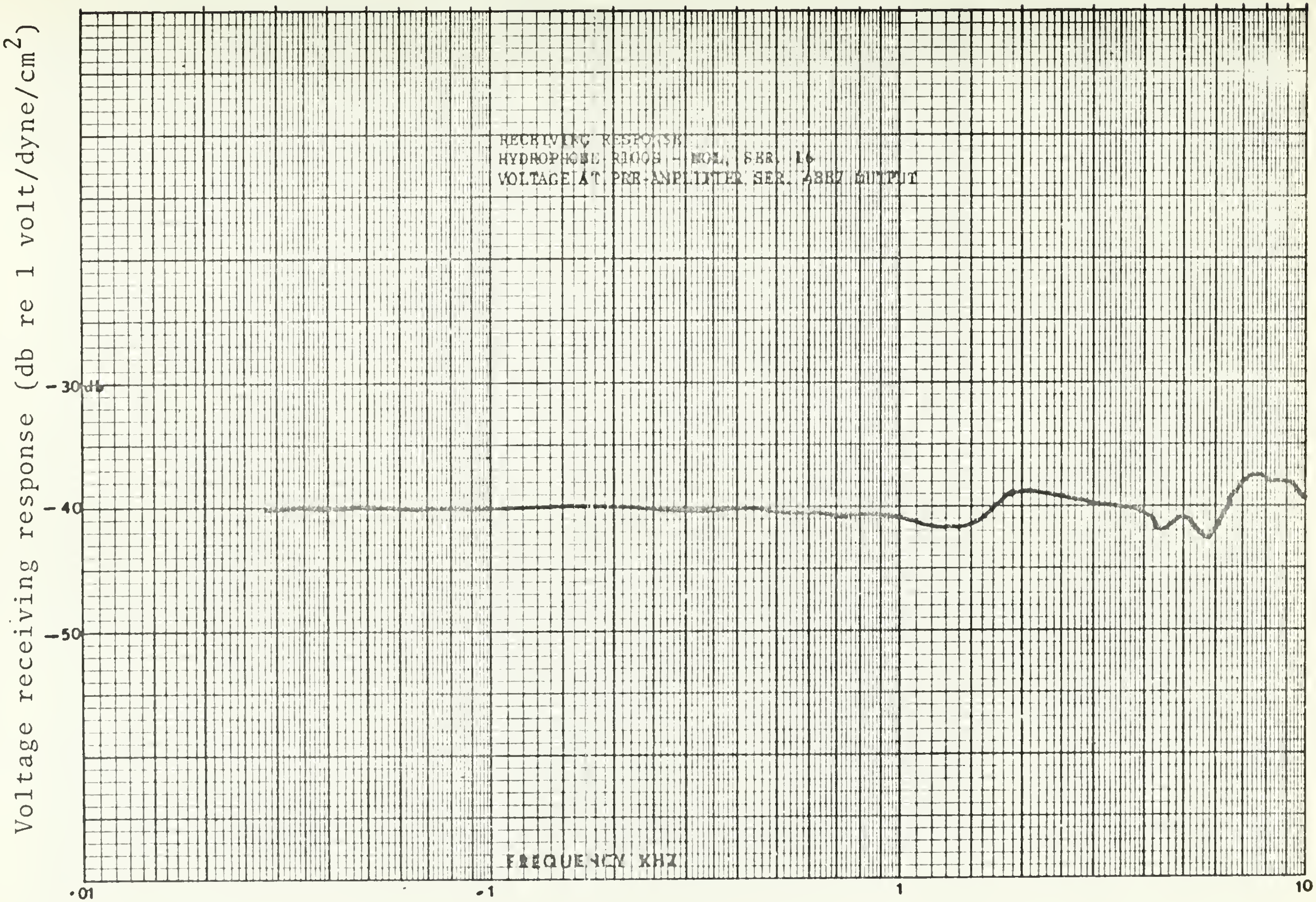

Figure 23. Voltage receiving response for the low-frequency hydrophone pre-amplifier combination.

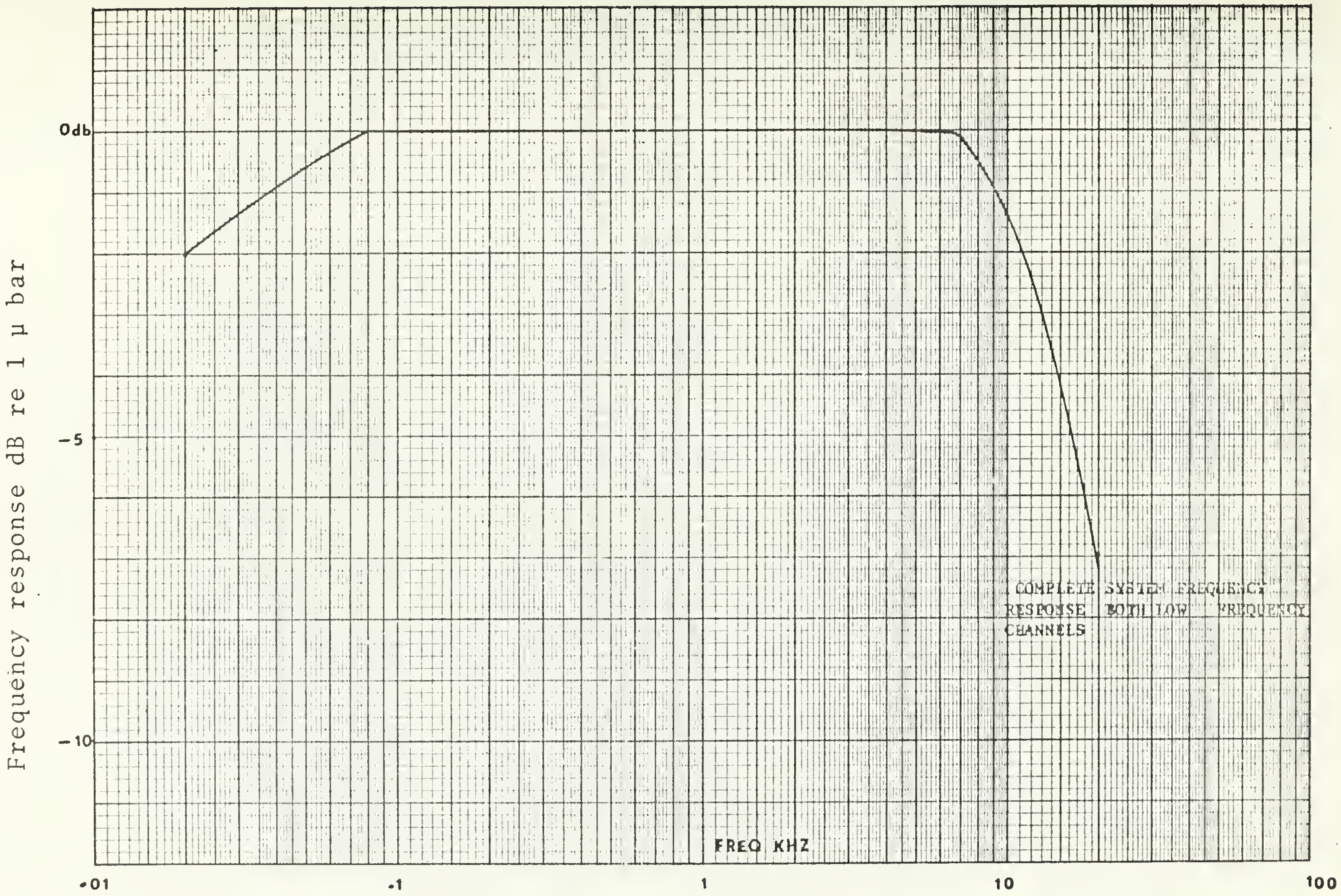

Figure 24. System frequency response for both low-frequency channels.

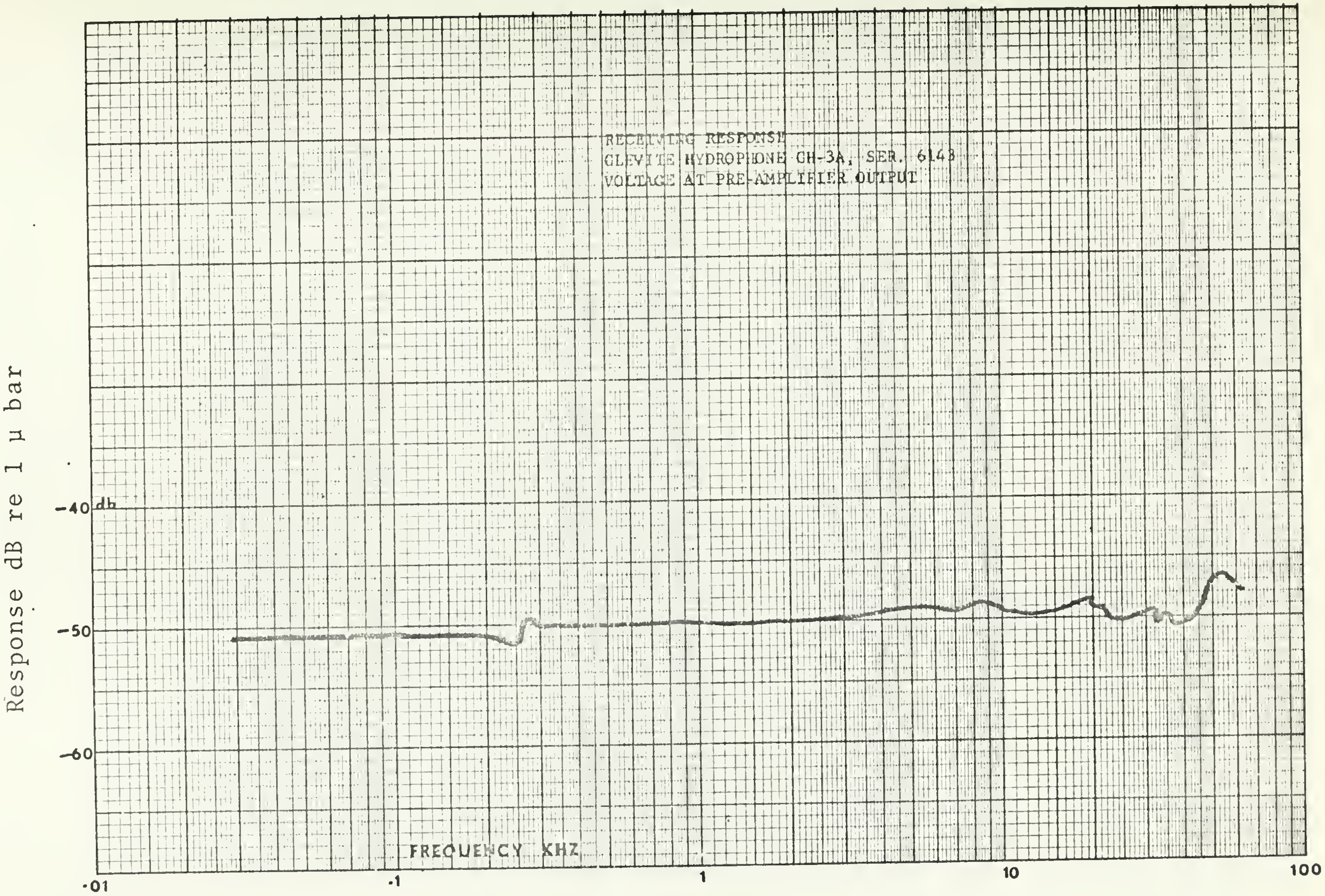

Figure 25. Voltage receiving response for the high-frequency system.

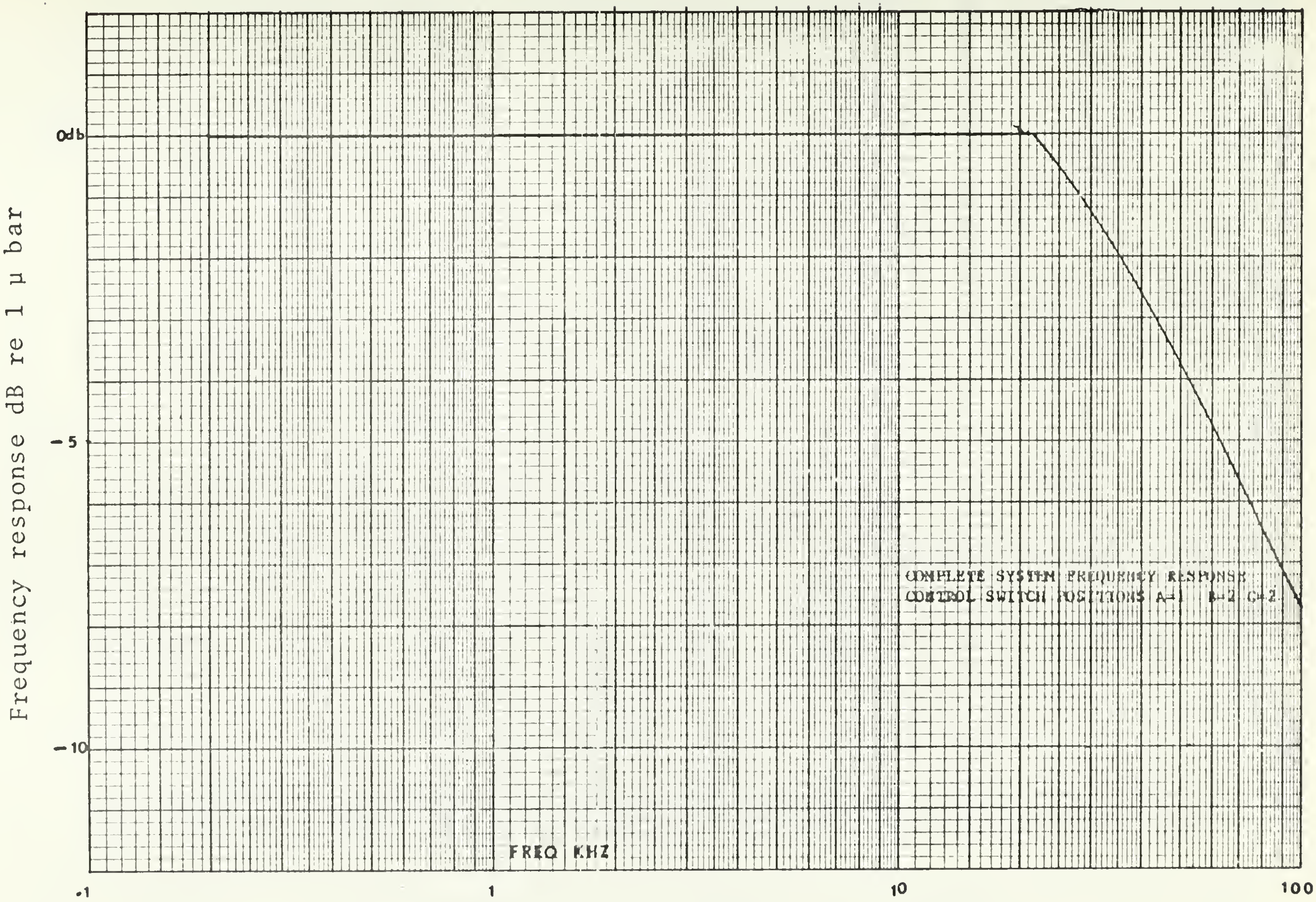

Figure 26. High-frequency system response for bandpass 30 Hz to 60 kHz.

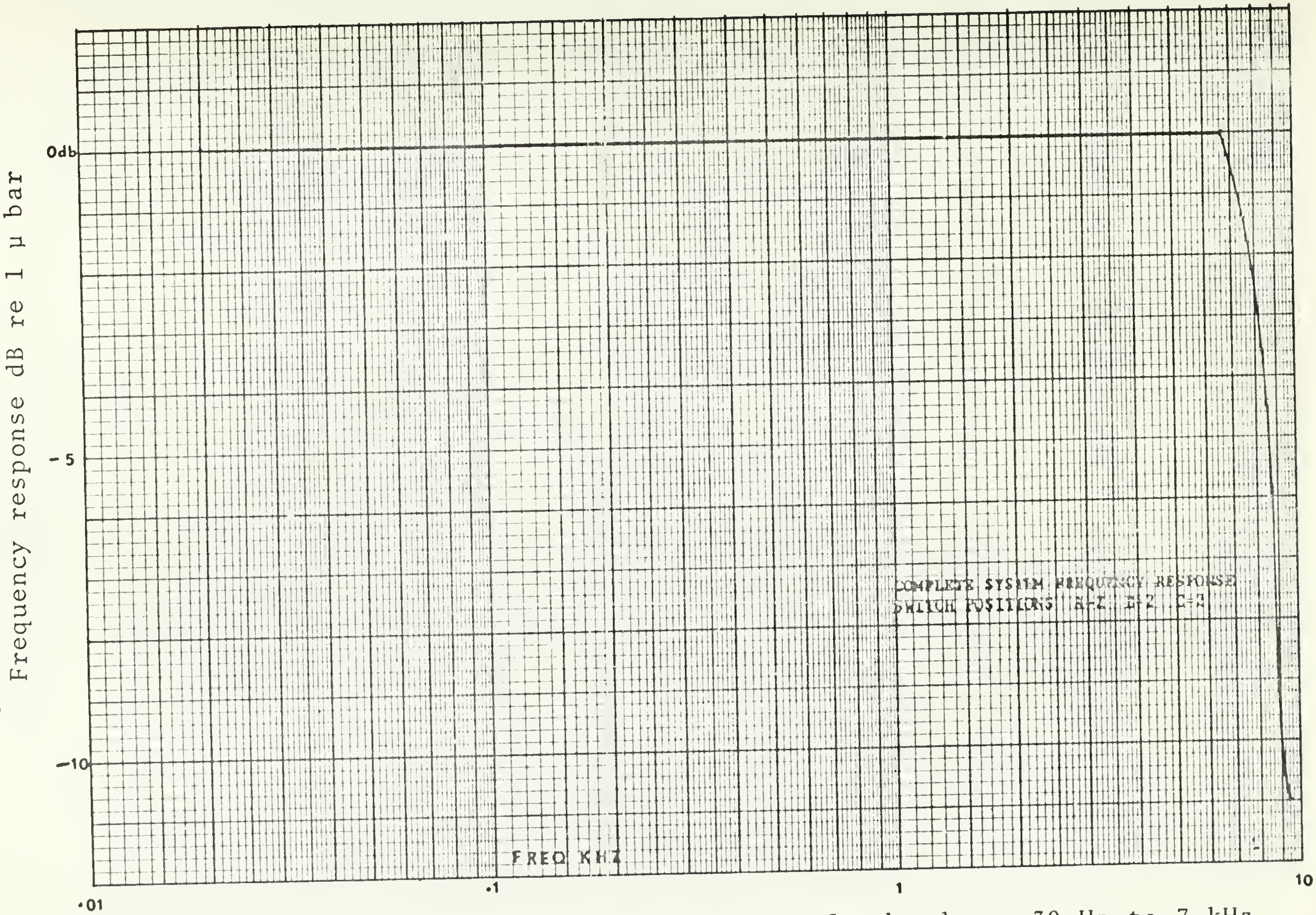

Figure 27. High-frequency system response for bandpass 30 Hz to 7 kHz.

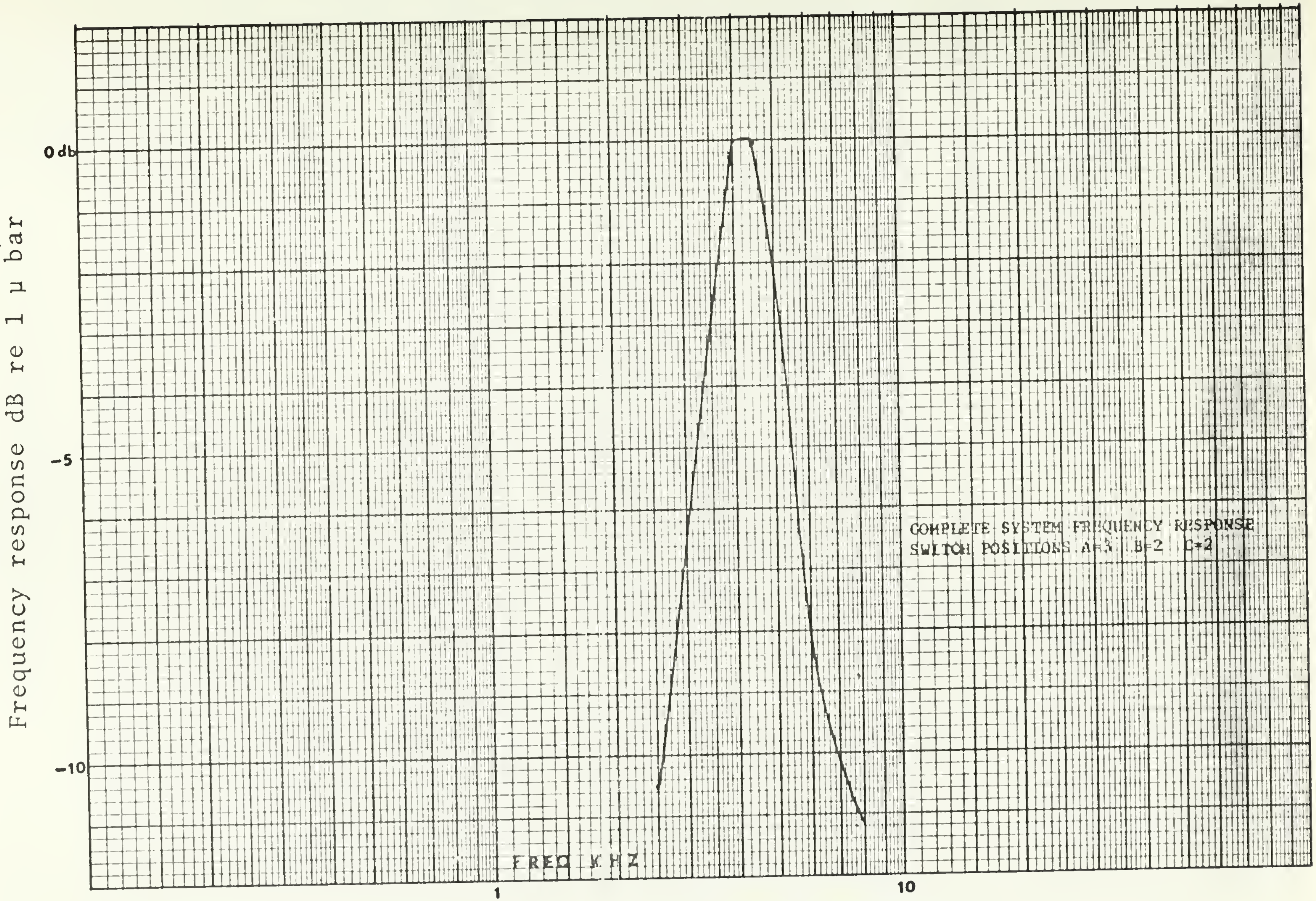

Figure 28. High-frequency system response for bandpass 30 to 6 kHz.

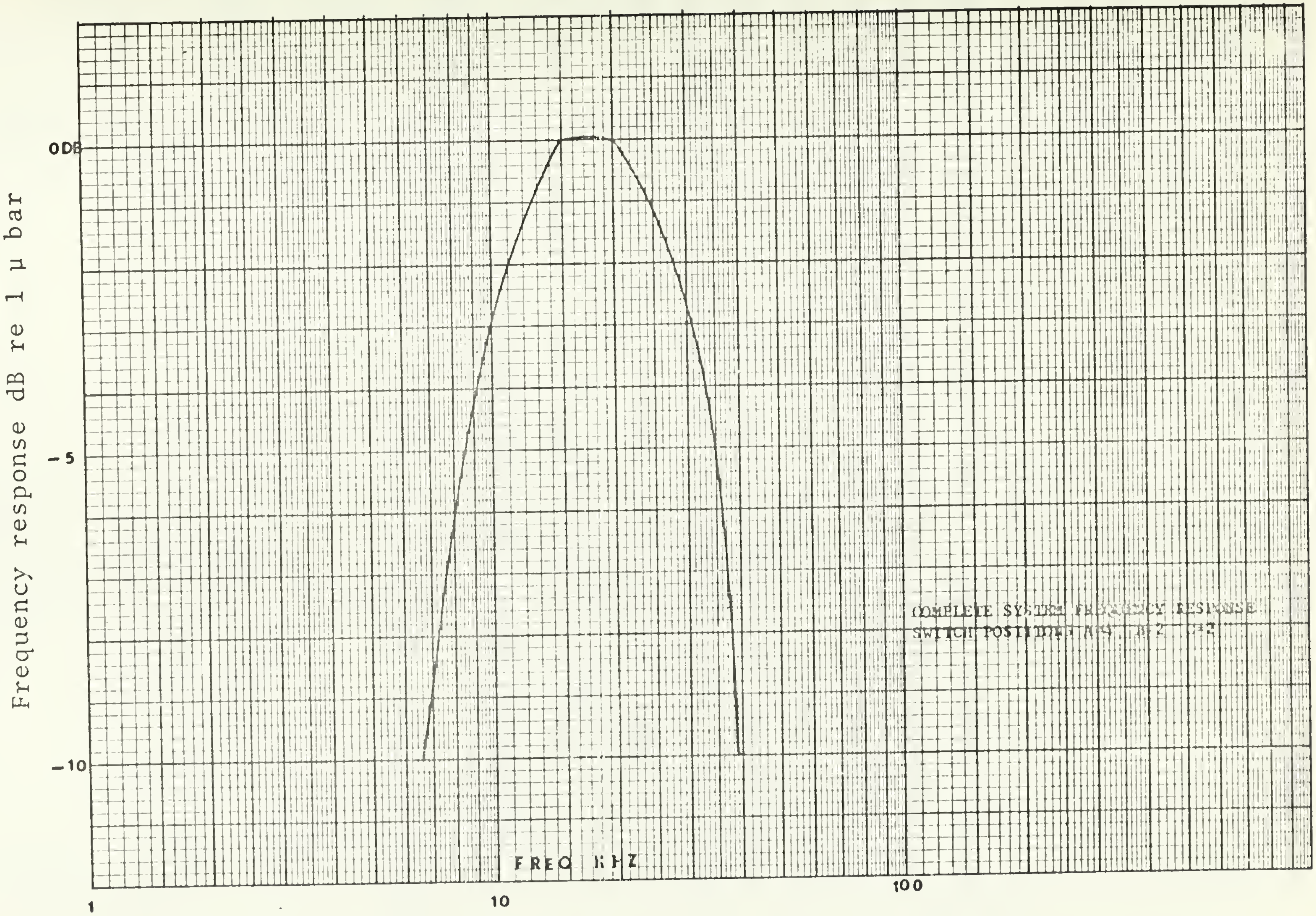

Figure 29. High-frequency system response for bandpass 10 to 30 kHz.

frequencies for the low-frequency channels are 320 kHz and 200 kHz, and the high-frequency carrier is 1.6 MHz. These signals are placed on the cable and detected on shore by discriminators which make the information available for recording or display.

Recordings were made with an Ampex model 1100 tape recorder equipped with ESR 1000 electronics. Normal operations used channels 1 and 3 for frequency modulated low-frequency inputs. Channel 2 amplitude modulated data from the high-frequency channel. Channels 4 to 6 were available to record ARL system data while channel 7 was used to record voice commentary. The system also includes a built-in monitoring system that permits audio and video display of incoming signals.

B. ANALYSIS EQUIPMENT AND CALIBRATION PROCEDURES

The following equipment was used to reduce the NOL ambient noise data:

1. A sangamo Model 3562 tape recorder converted to one half inch operation [Ref. 12].

2. A Hewlett-Packard Wave Analyzer Model 302A with attached Sweep Drive Model 1297A [Refs. 13 and 14].

3. A Hewlett-Packard Wave Analyzer Model 3590A with a plug-in Sweeping Local Oscillator Model 3594A [Ref.s 15 and 16].

4. One Krohn-Hite filter Model 3340.

5. A Varian Model F 120 X-Y Plotter [Ref. 10].

Auxiliary calibration and monitoring facilities were provided by a Wavetek signal generator Model 134, a Hewlett-Packard oscilloscope Model 120B, Hewlett-Packard vacuum-tube voltmeter Model 400L and an audio amplifier-speaker combination.

Wave analyzers were selected in preference to octave-band filters because they provided greater flexability. Although both wave analyzers covered the frequency range of interest, Model 302A was used over the range 40 to 1,000 Hz while Model 3590A was used to examine frequency ranges above 400 Hz. A 6-Hz bandpass with a 17 Hz/sec sweeprate and a 100-Hz bandpass with a 100 Hz/sec sweeprate were the primary operating modes for Models 302A and 3590A respectively. The 100 Hz/sec sweeprate and the time sweep scales of the X-Y plotter that operate in multiples of 10 sec/inch reduced the time required to change frequency scales when operating with Model 3590A.

The X scale was calibrated to respond to a linear output voltage from the sweep drives of the wave analyzers corresponding to the frequency ranges being swept. However, when frequency ranges in excess of 4,000 Hz were swept, substituting the X-Y plotter internal time sweep mode in place of the Model 3590A, sweeping local oscillator output caused no reduction in accuracy.

The Y axis of the plotter was driven by linear voltage outputs of the wave analyzers. The linear Y output from model 3590A is 10 volts corresponding to full-scale meter deflection, regardless of the voltage range being measured.

This feature is compatible with the fixed Y scales of the plotter which are multiples of 10 volts/inch. Y axis output from Model 302A is also a linear function of meter deflection, but it requires to be matched with an impedance less than 1,500 ohms. To match this output to the high input impedance of the plotter, a 640 ohm resistor was placed in parallel with the plotter input. The resulting voltage did not correspond to any of the fixed plotter scales; therefore, a careful vernier adjustment of scale values was required to ensure accurate results.

The arrangement of analysis equipment was as shown in Figure 30. The Khron-Hite filter between the tape recorder output and wave analyzer input was used alternately in a low or high pass mode to avoid the display of a persistent 25-kHz signal, generated within the recording equipment.

The system was calibrated prior to each analysis session. After the wave analyzers had been aligned in accordance with manufacturers' specifications, a signal of constant level and frequency was supplied from the Wavetek signal generator in place of the normal tape recorder input. The wave analyzer was then tuned to give maximum response, and the level was checked against the input level. The wave analyzer output was then applied to the Y axis of the plotter while an internal time sweep was applied to the X axis. Zero and vernier adjustments were made to give the correct level. A typical calibration plot from the Model 3590A (Figure 31) shows that a 51-millivolt signal is reproduced at 5.1 $\pm$.05

volts with a plotter scale of 2 volts/inch network ensures accuracy for scale multiples of these basic divisions.

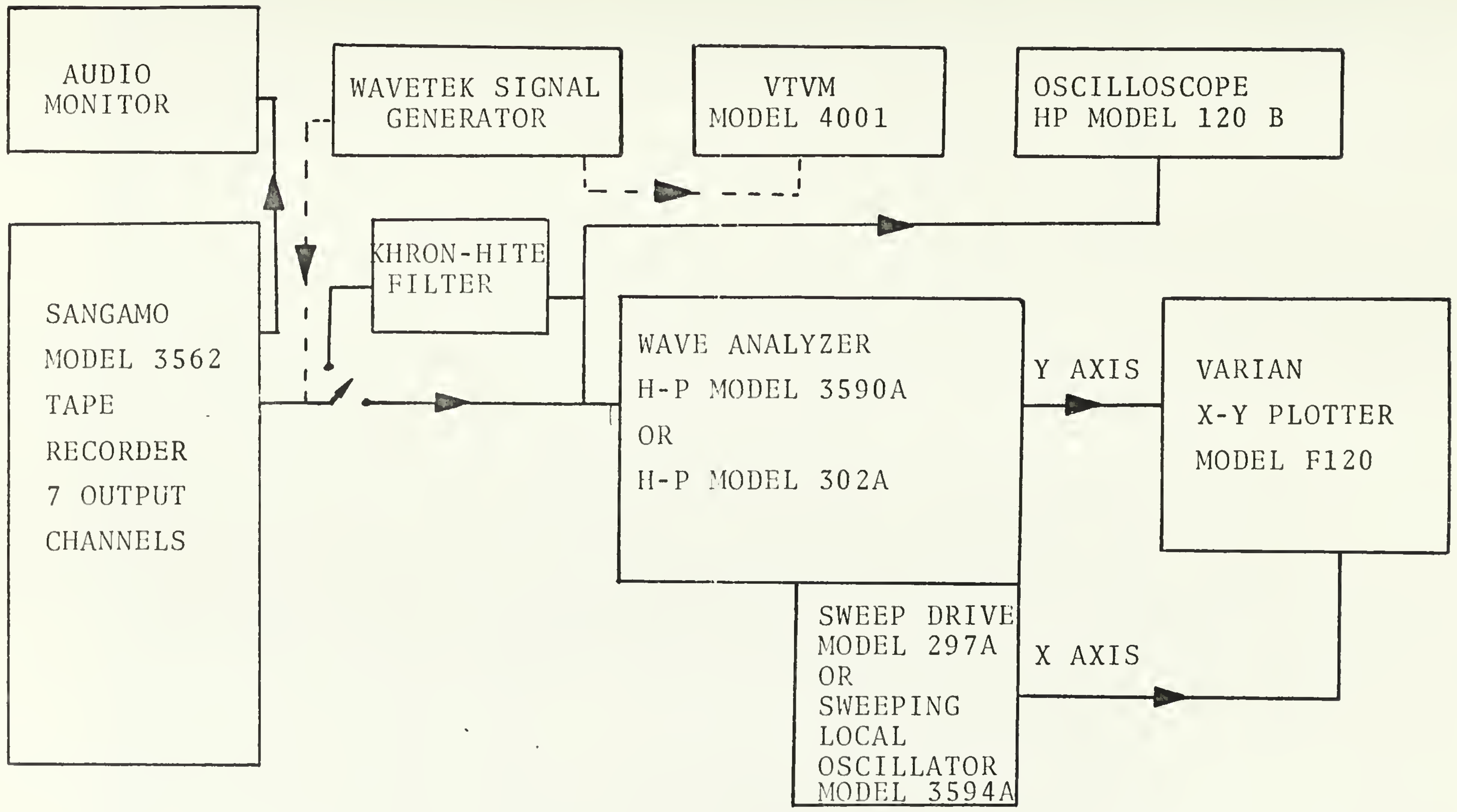

Figure 30. Block diagram showing equipment arrangement for data analysis. Dashed lines indicate connections to be made for calibration.

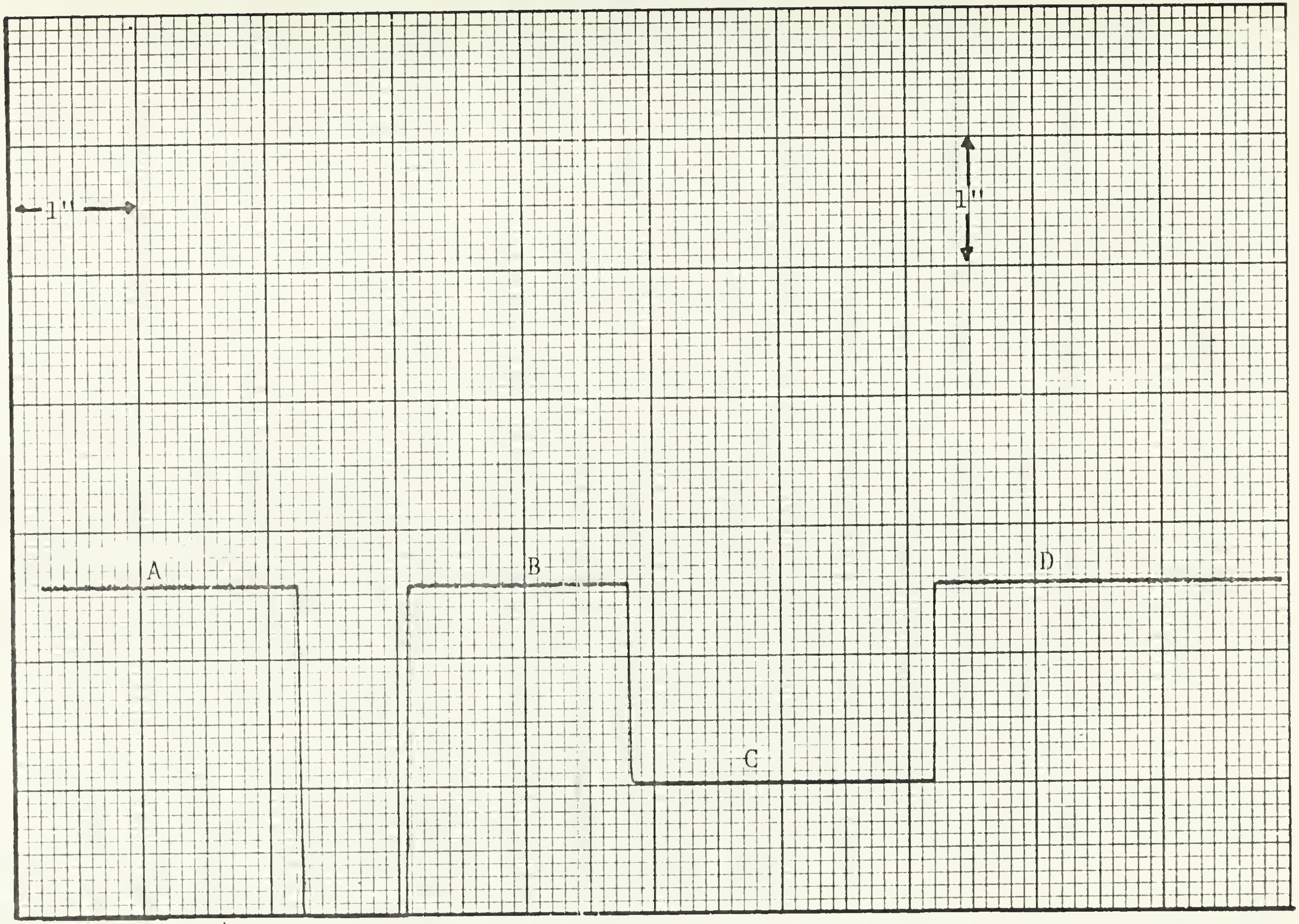

Figure 31. Analysis equipment calibration plot. Plotter calibration measured input 51 millivolts. A, B, D have plotter scale 2 volts/inch. C has plotter scale 5 volts/inch.

V. REDUCTION OF DATA

A. REFERENCE LEVELS

A 4-kHz calibration signal was placed on each tape before recording ambient noise data, in order to provide a true reference for setting the electronics in the play-back recorder. These calibration signals were recorded with the NOL control panel set at A1 B1 C1. The normal gain with such settings is zero decibels; however, the primary high-frequency channel had been replaced with the spare channel which provided a 6 dB gain in position B1. Levels determined using the calibration signal as a zero gain reference between record and reproduce systems had, therefore, to be reduced by 6 dB for high-frequency channel data.

Cape North calibration inputs were 0.485 volts rms or 1.37 volts peak-to-peak for low-frequency channels and 0.970 volts rms or 2.74 volts peak-to-peak for the high-frequency channel. The amplitude modulated electronics of the Sangamo recorder could readily be adjusted to match the output to the calibration level; however, adjustment of the frequency modulated electronics was not easily achieved without several operations. Therefore, a correction factor was determined based on the difference between the input at Cape North and the reproduced output. A typical calibration record (Figure 32) indicates a mean high-frequency level of

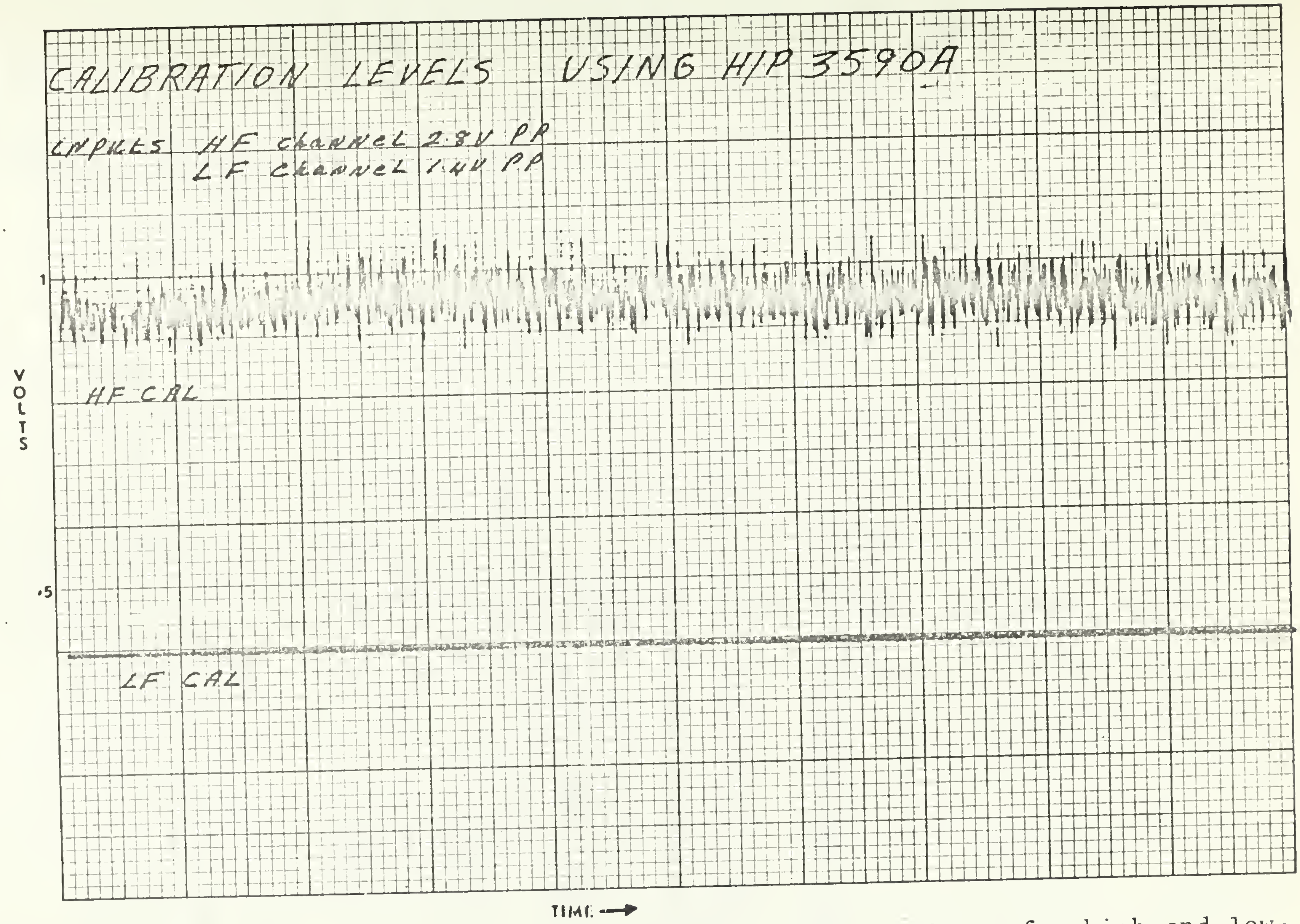

Figure 32. Calibration voltages at output of wave analyzer for high and low-frequency channels.

0.960 volts rms, approximately one per cent lower than the input level. The low-frequency calibration signal was set at 0.485 volts at Cape North; the output of the wave analyzer was 0.400 volts. A calibration correction of ± 1.5 dB was therefore applied to all low-frequency channel spectrum levels. The correction was based on the relationship level in dB = 20 log $\frac{V2}{V1}$.

B. INITIAL OUTPUT AND REDUCTION PROCEDURE

Three sets of records were produced from the noise signal on each tape:

1. A voltage versus frequency plot (Figure 33). This graph presents the noise voltage as a function of frequency and permits a realistic although relative appreciation of the spectral energy distribution. These plots were repeated at different tape positions (Figure 34) to assess the change of spectral energy density with time. For example, Figures 34a and 34b show how the noise voltage in the frequency range 1 to 6 kHz had changed over a two-minute interval.

2. A plot of noise voltage versus time at a particular frequency (Figure 35). These plots were either 100 or 200 seconds in duration, and when repeated at different positions along the tape, they indicate the relative stability of the noise level for the particular frequency. Figure 35 indicates that the mean voltage at 35 kHz varied from 13 to 25 millivolts over a 200-second interval. This variation

corresponds to 5.7 dB which which is a large change at this high frequency.

3. The third output form (Figure 36) was the basic record from which the noise spectra were produced. This consists of setting the wave analyzer at a particular center frequency and manually positioning the pen along the X-axis of the plotter. The analyzer output then produced a vertical line showing the maximum and minimum voltage reached during the 20-second sample time. The mean voltage was reported from the meter reading of the wave analyzer.

Parameters available after the initial output plots had been produced were:

1. Voltage level in millivolts.
2. Overall system gain.
3. Hydrophone voltage receiving response.
4. Frequency response of the system for any given filter position.
5. Bandwidth of the analyzer.

The following relationships were employed to calculate spectrum levels

1. The output voltage level (V2) and the system gain (G) were combined using the formula $G = 20 \log \frac{V2}{V1}$ to find the voltage level (V1) at the hydrophone pre-amplifier output terminals.

2. The hydrophone voltage receiving response (M) is usually stated as the number of decibels relative to 1 volt produced by an rms acoustic pressure of 1 dyne/cm^2 [Urick, 1969].

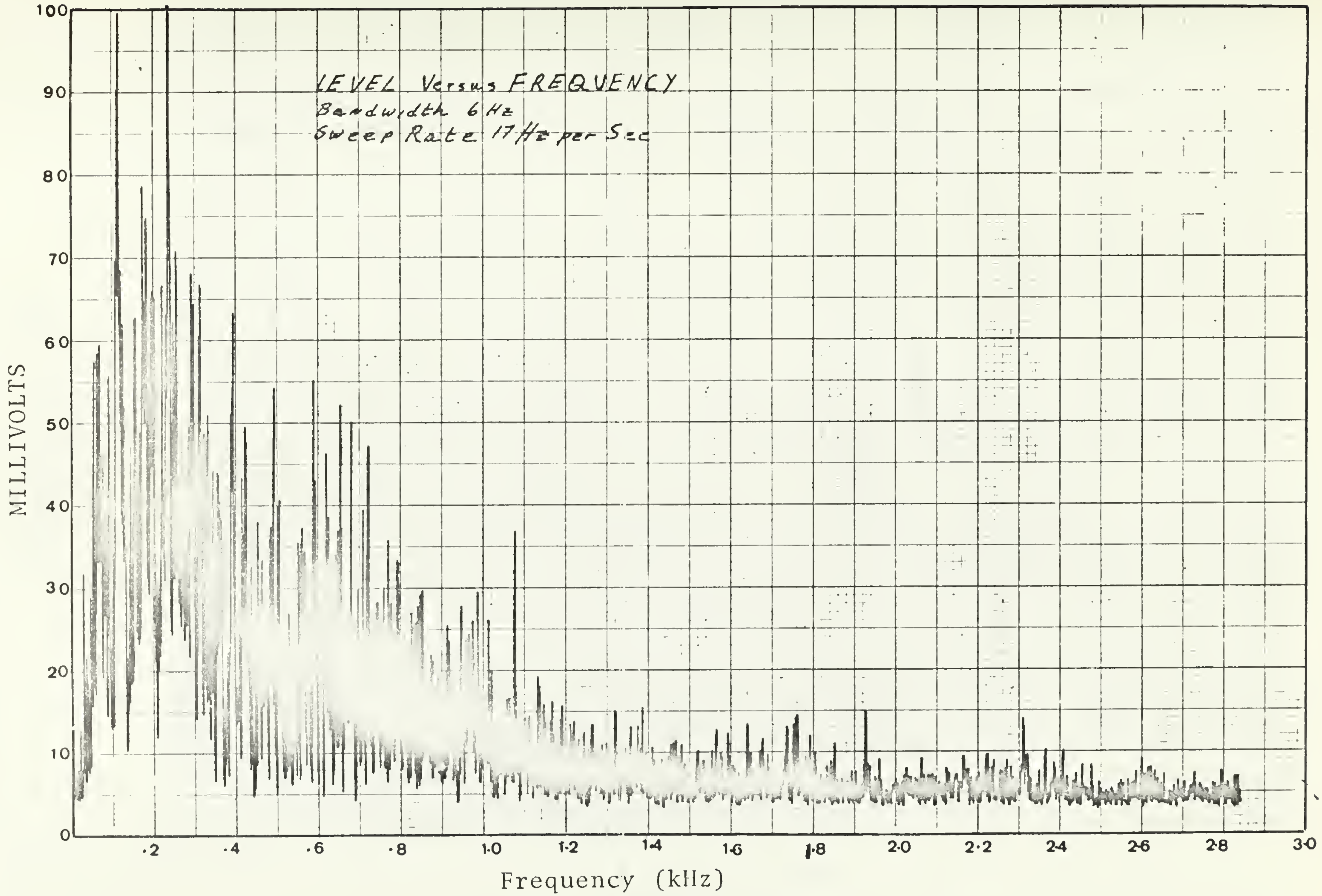

Figure 33. Voltage level versus frequency plot.

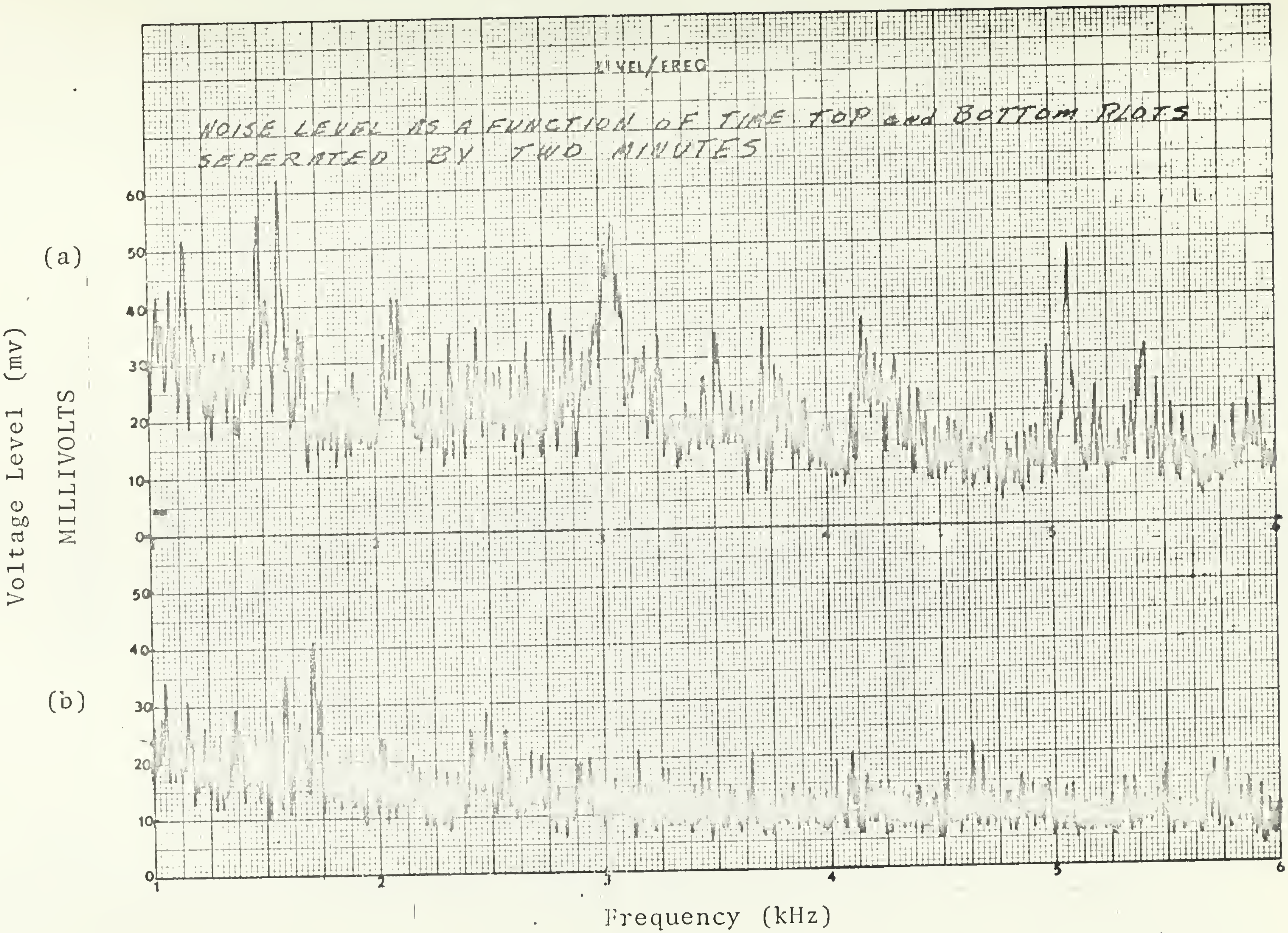

Figure 34. Voltage level versus frequency in the range 1 to 6 kHz, showing time change of noise signal.

Figure 35. Voltage level versus time plot at 35 kHz.

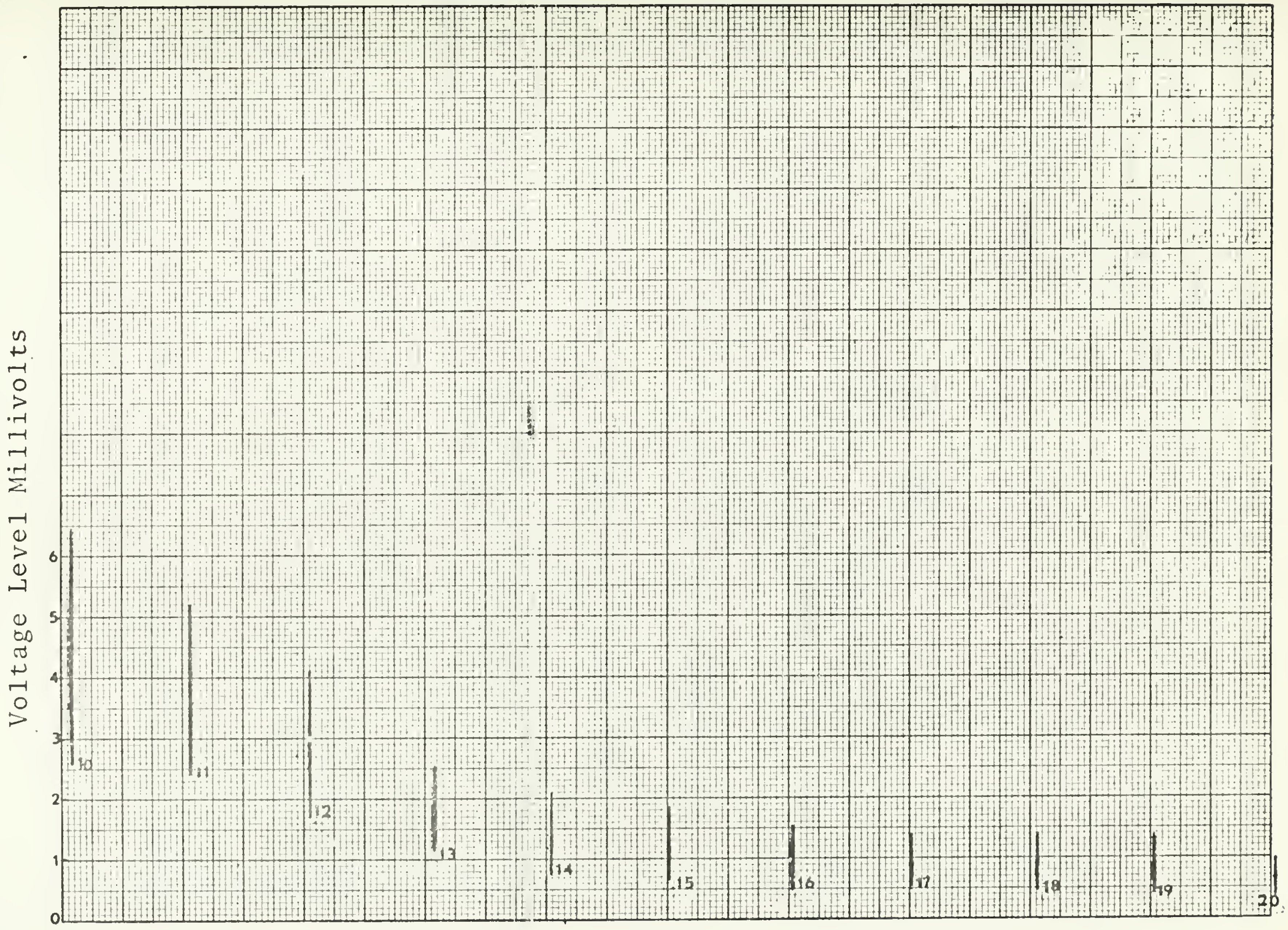

Figure 36. Plot showing range of values at discrete frequencies over a 20-second sample time.

Thus a response stated as -40 dB re 1 volt means that an open circuit rms voltage (V) of 10^{-2} volts is generated by an rms pressure of 1 dyne/cm^2. Therefore, by knowing the response and reference pressure, it is possible to find the equivalent reference voltage. Then by using the ratio:

$$\frac{V}{P_{ref}} = \frac{V1}{P}$$

the actual rms pressure at the hydrophone can be determined since V1 was previously calculated.

3. Band level (BL) in decibels is defined as:

$$BL = 20 \log \frac{P}{P_{ref}} \quad \text{where } P_{ref} = 1 \ \mu \text{ bar}$$

4. The spectrum level (SPL) is determined from the band level by applying a bandwidth (W) correction.

$$SPL = BL - 10 \log W$$

5. In order to work with millivolts instead of volts, a scale factor of -60 dB/ μ bar is inserted in the final equation.

By eliminating common factors between the above equations, the spectrum level may be represented as:

$$SPL = 20 \log V2 - 60 - M - G - 10 \log W.$$

For example, if V2 = 32 mv, M = -40 dB/ μ bar, G = +40 dB, and W = 7, the spectrum level is -38.478 dB/ μ bar.

Noise signals recorded simultaneously produced significantly different spectrum levels depending on whether the high

or low frequency hydrophone data was presented (Figure 37). However, when the calibration corrections detailed earlier in this section were applied, both systems produced a very similar spectrum (Figure 38).

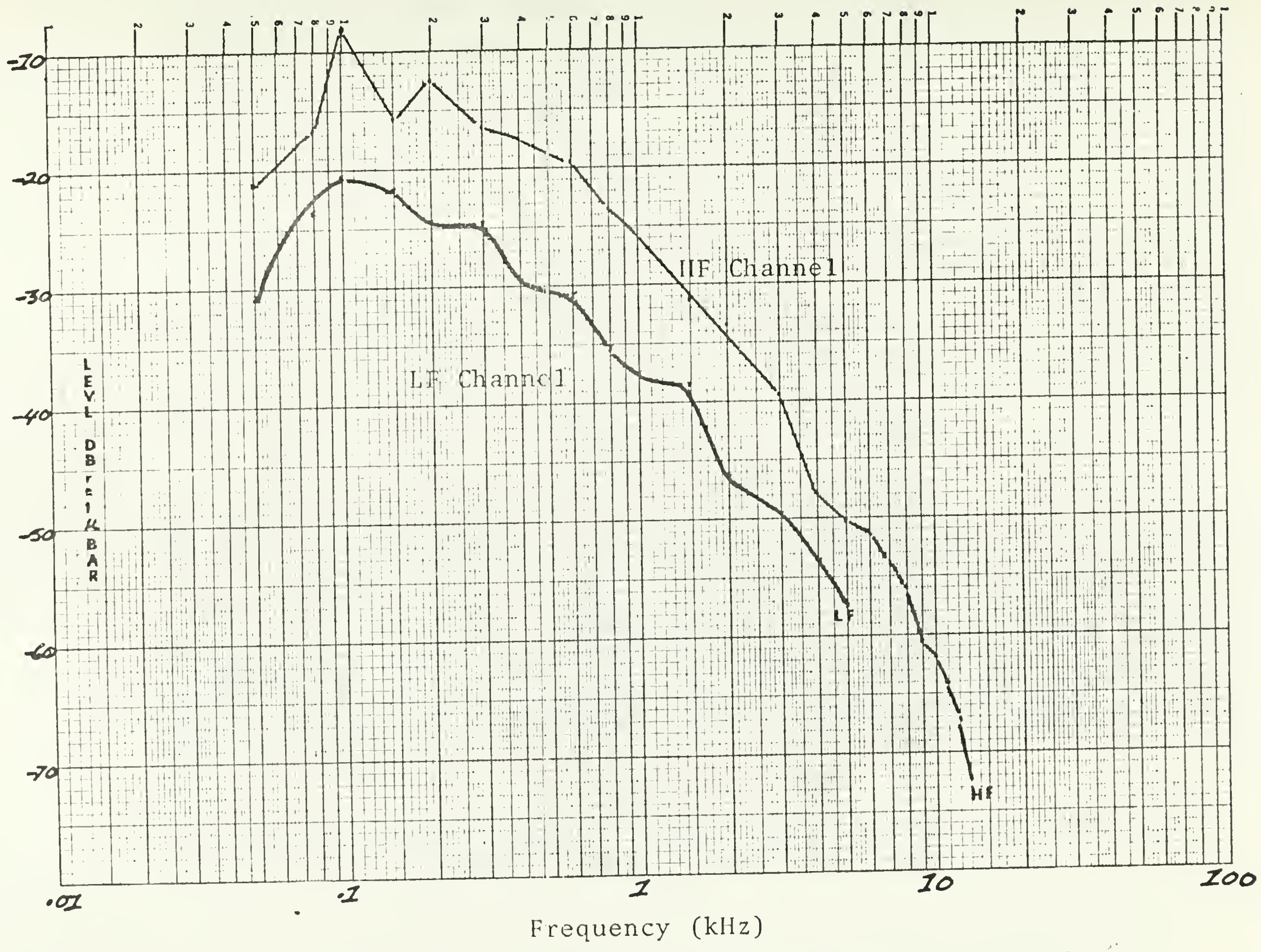

Figure 37. Spectrum levels obtained by high-frequency and low-frequency hydrophones before calibration corrections.

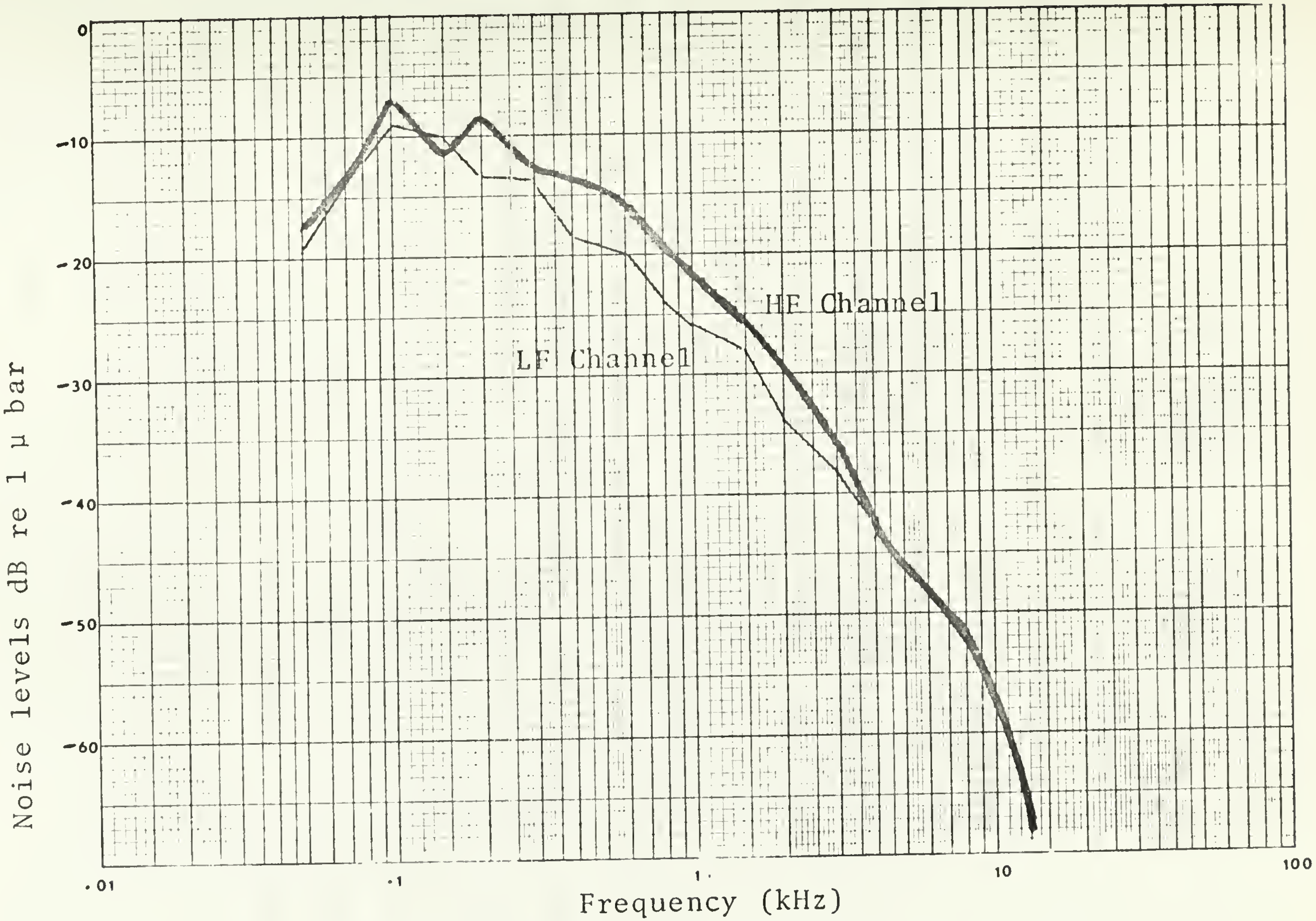

Figure 38. Spectrum levels plotted from high and low-frequency channels after calibration corrections.

VI. DISCUSSION OF DATA

Normal noise conditions indicate a continuous spectrum with higher energy levels in the low-frequency region. The frequency range from 200 to 400 Hz was examined using a 6 Hz and a 100 Hz bandwidth. Spectrum levels calculated from mean readings in each band varied by only $\pm.2$ dB. However, perturbations of ± 12 dB were typical when a 6-Hz bandwidth was used, these were reduced to ± 4 dB for a 100-Hz bandwidth. These observations coupled with the absence of line components suggest that at any given frequency large random fluctuations occur about a mean. The bandwidth chosen for analysis must be narrow enough to show variations in spectrum level as a function of frequency but not so narrow that random short duration noise amplitude changes obscure or make the mean level difficult to obtain. To adequately delineate frequency dependence below 200 Hz, a bandwidth of not greater than 10 Hz with a sweeprate of not greater than 20 Hz/sec was found to be satisfactory, while a 100-Hz bandwidth and a sweeprate of 100 Hz/sec is ample to investigate the higher frequency regions of the spectrum.

A characteristic difference between ambient noise profiles under conditions of ice cover and open water is the occurrance of large random changes in mean level throughout the entire spectrum. Voltage lever versus time plots (Figures 39

to 41) show that, except for some prominant spikes in the 500-Hz plot, the mean level is relatively stable under open water conditions. Similar plots for conditions of ice cover (Figures 42 to 47) show that mean voltage levels below 500 Hz are relatively stable, while at higher frequencies wide variations in mean levels occur over short time intervals. These changes are apparent at all frequencies throughout the spectrum. For example, the large negative excursion followed in 40 seconds by a relative maximum is a readily identified feature in both the 35-kHz (figure 46) and 50-kHz (Figure 47) plots. The absolute level changes, however, decrease with increasing frequency. Greater attenuation losses at higher frequencies could account for such a decrease if the original source level at these frequencies were assumed to be equal. The relative stability of the low-frequency end of the spectrum and the instability in the high-frequency region indicate that the source of the instability is a feature of the ice cover in the immediate vicinity of the array, while low-frequency components from a much wider source area act to stabilize the low-frequency region. The level variations were most pronounced under conditions of ten tenths ice cover and when wind conditions caused ice convergence along the coast. The variations also correlated with a high-intensity groaning sound terminating in a sharp crack. Visual observations show that large cracks suddenly develop in ice floes subject to compression. It is proposed that compressional shear within the ice field

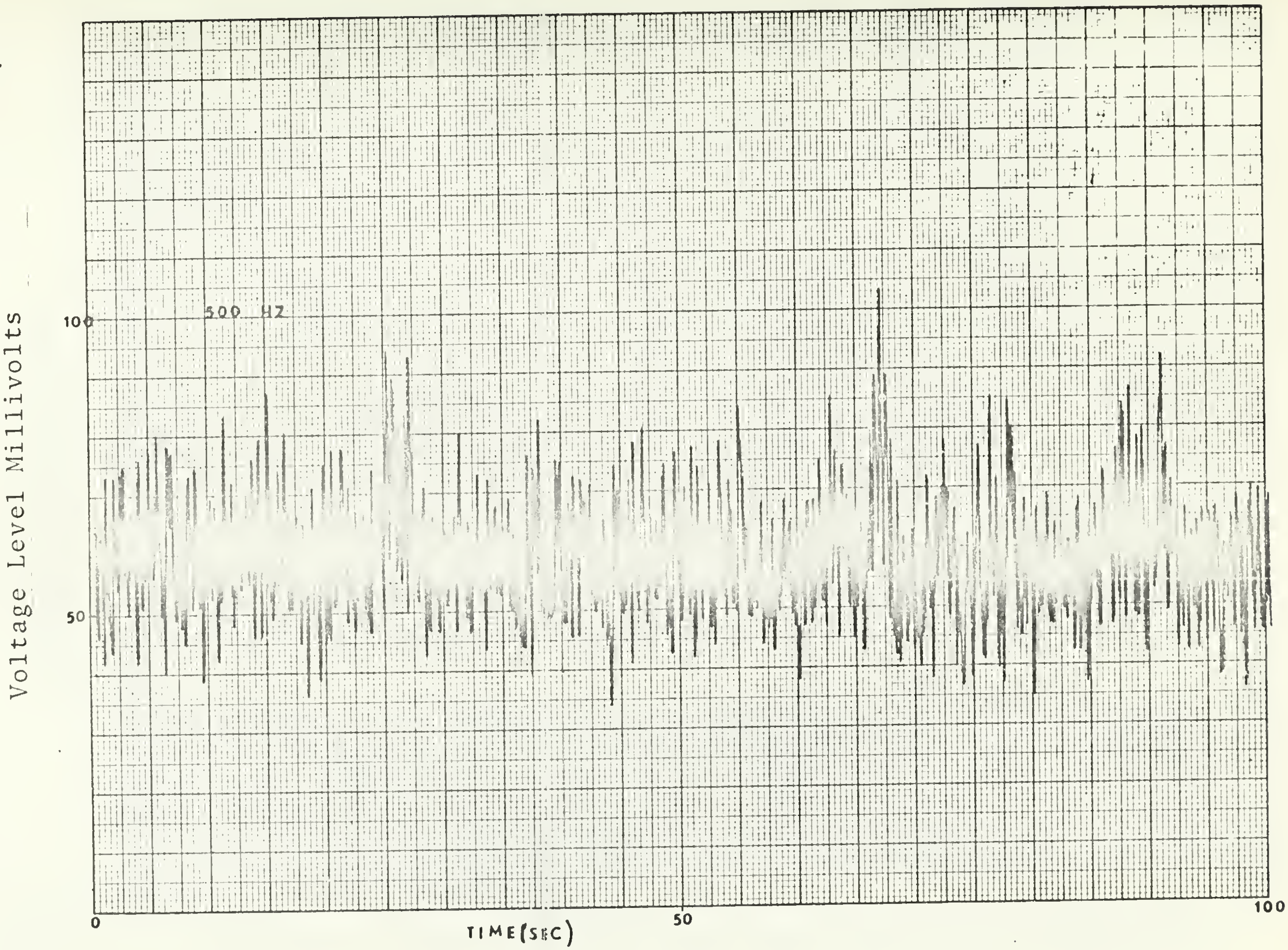

Figure 39. Level change at 500 Hz under open water conditions.

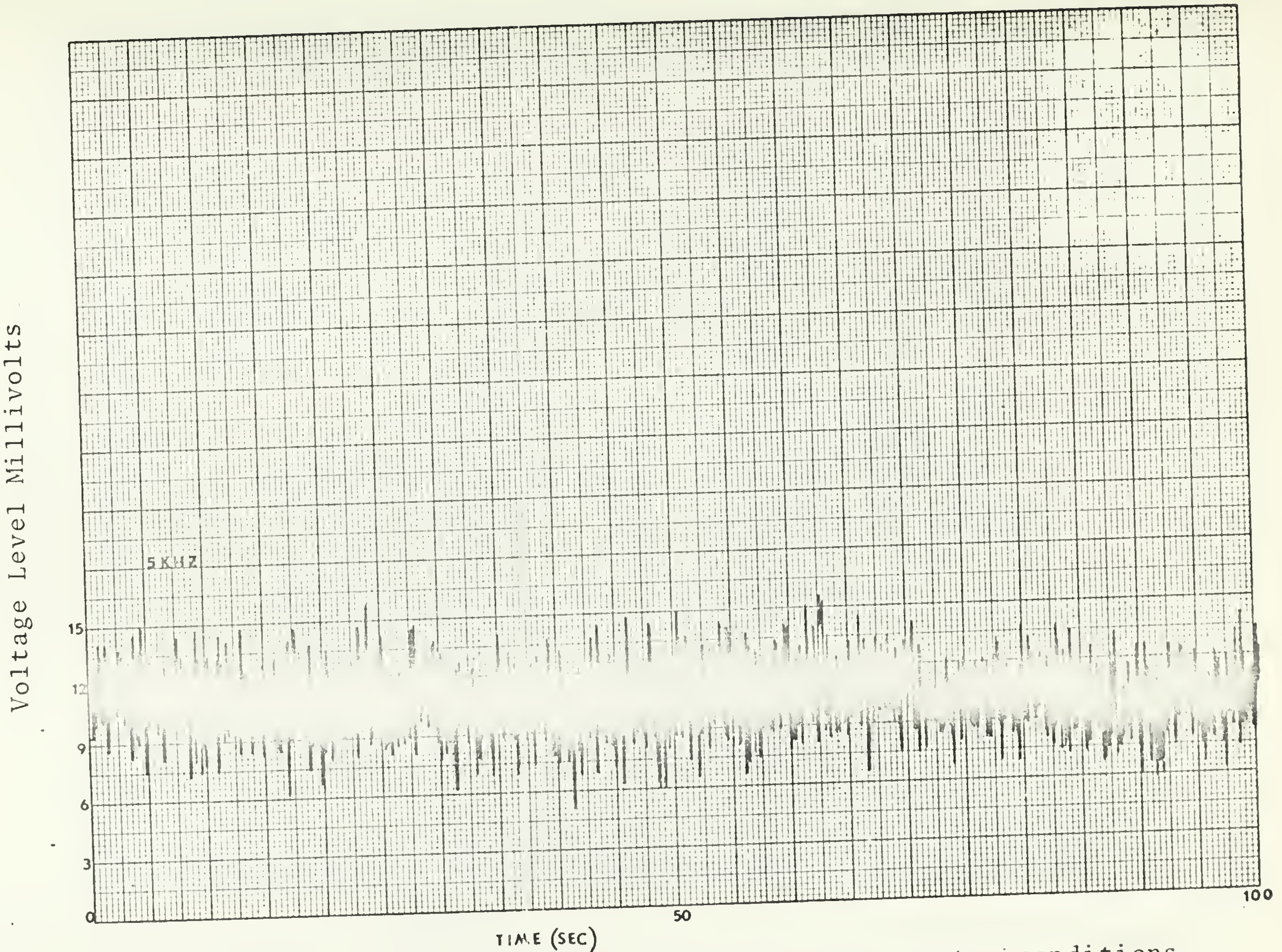

Figure 40. Level changes at 5 kHz under open water conditions.

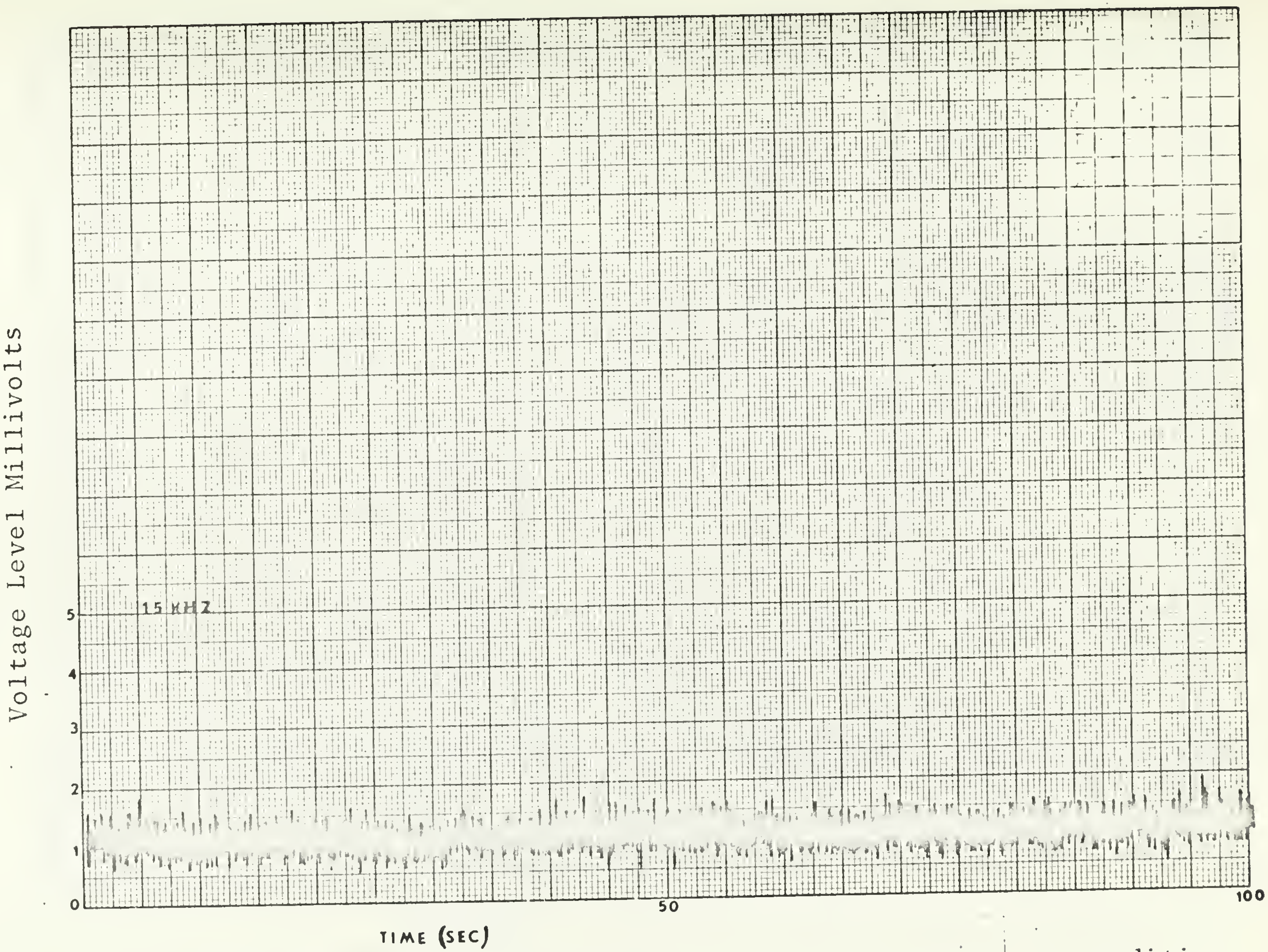

Figure 41. Level changes at 15 kHz under open water conditions.

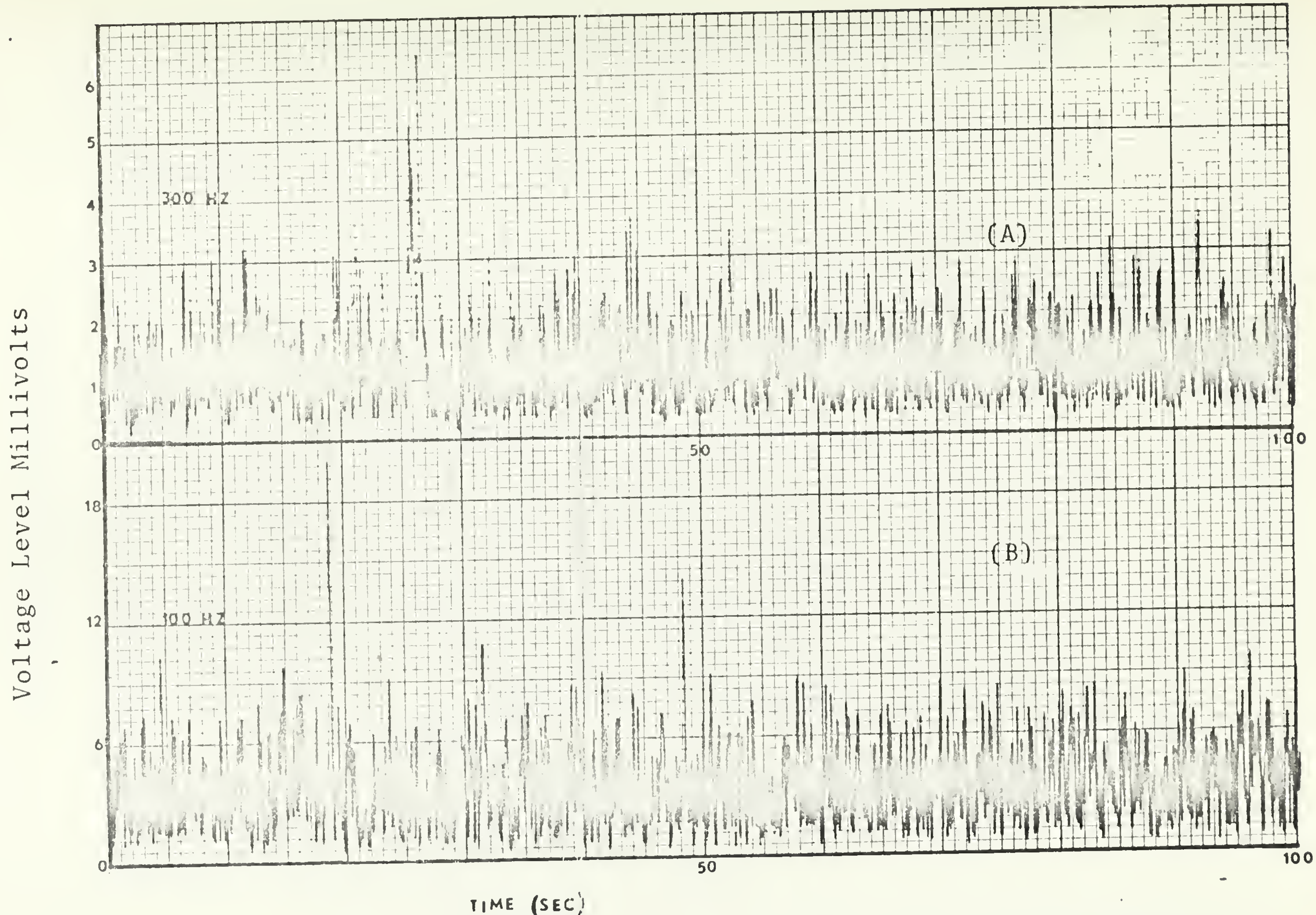

Figure 42. Level changes at 100 Hz & 300 Hz under ice cover.

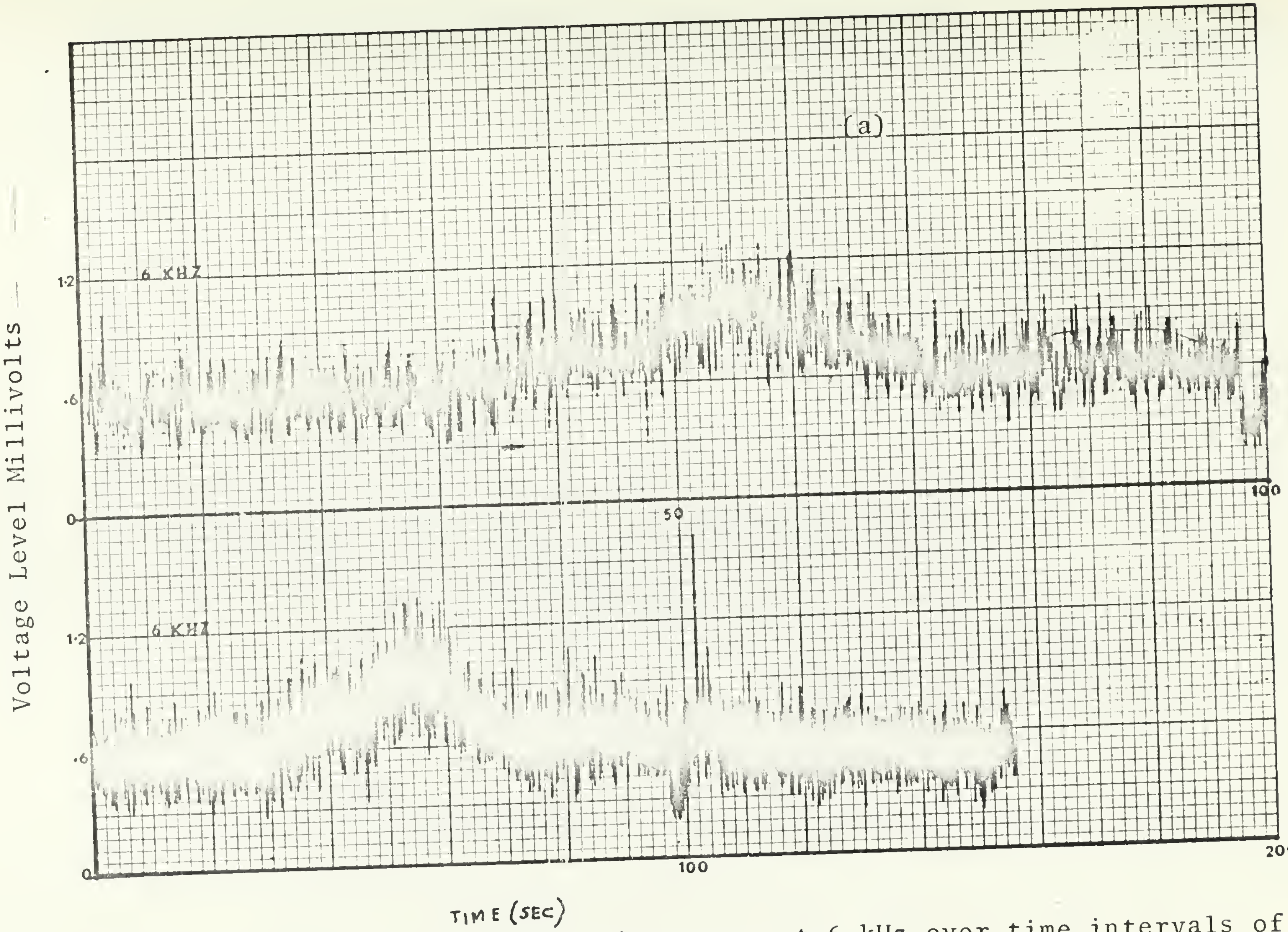

Figure 43. Level changes under ice cover at 6 kHz over time intervals of 100 seconds and 150 seconds. The same section of tape was used in each case.

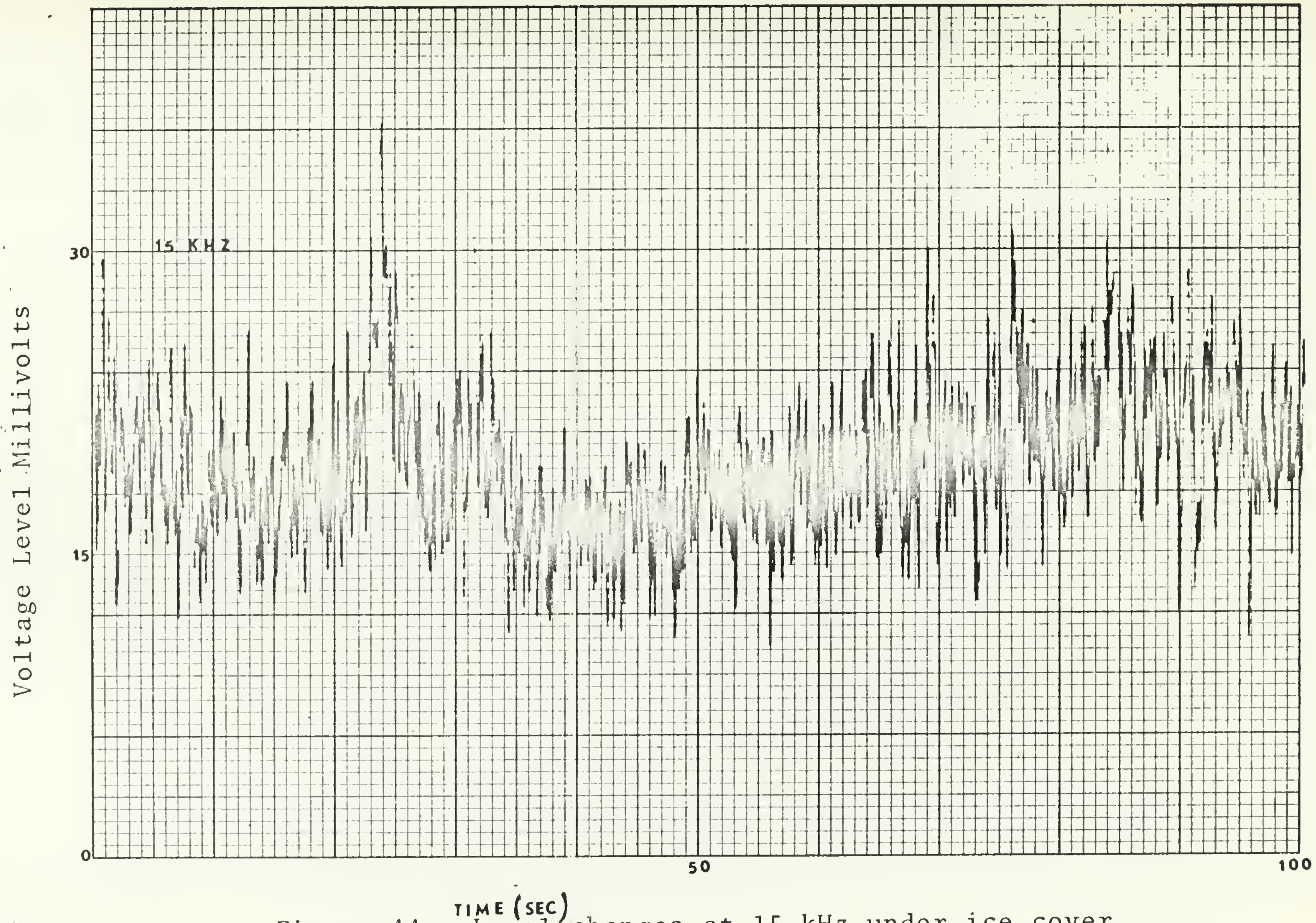

Figure 44. Level changes at 15 kHz under ice cover.

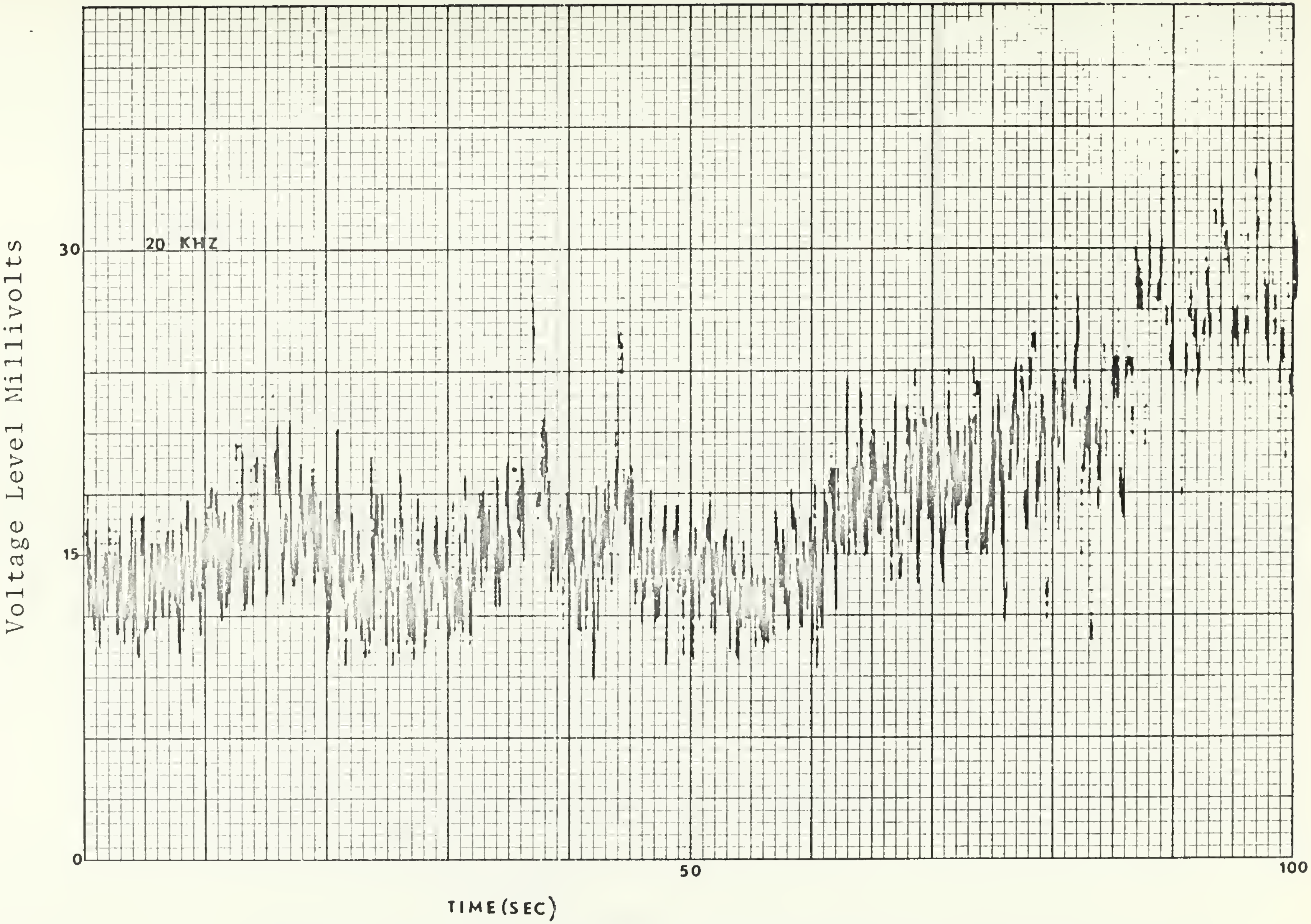

Figure 45. Level change at 20 kHz under ice cover.

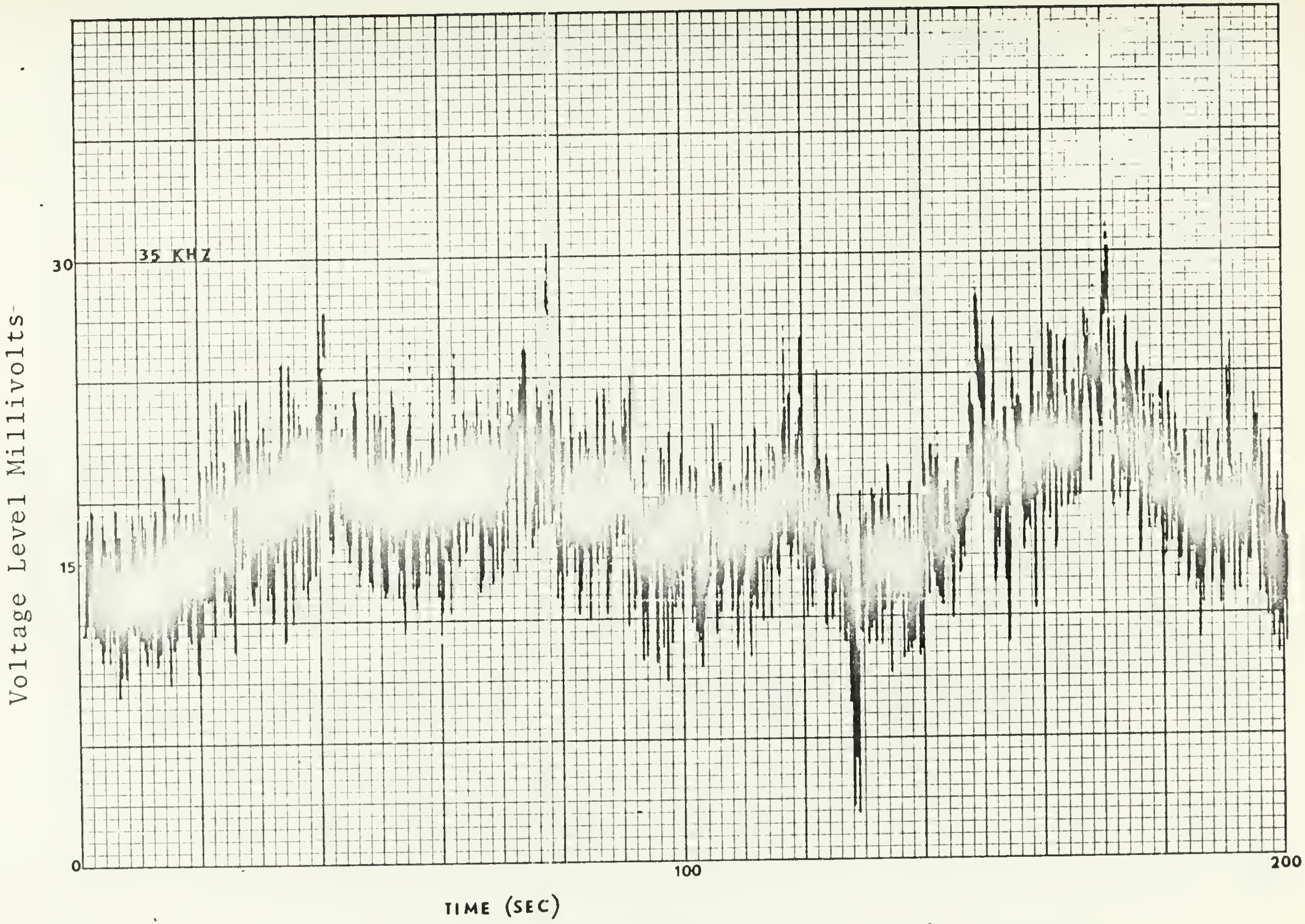

Figure 46. Level change at 35 kHz under ice cover.

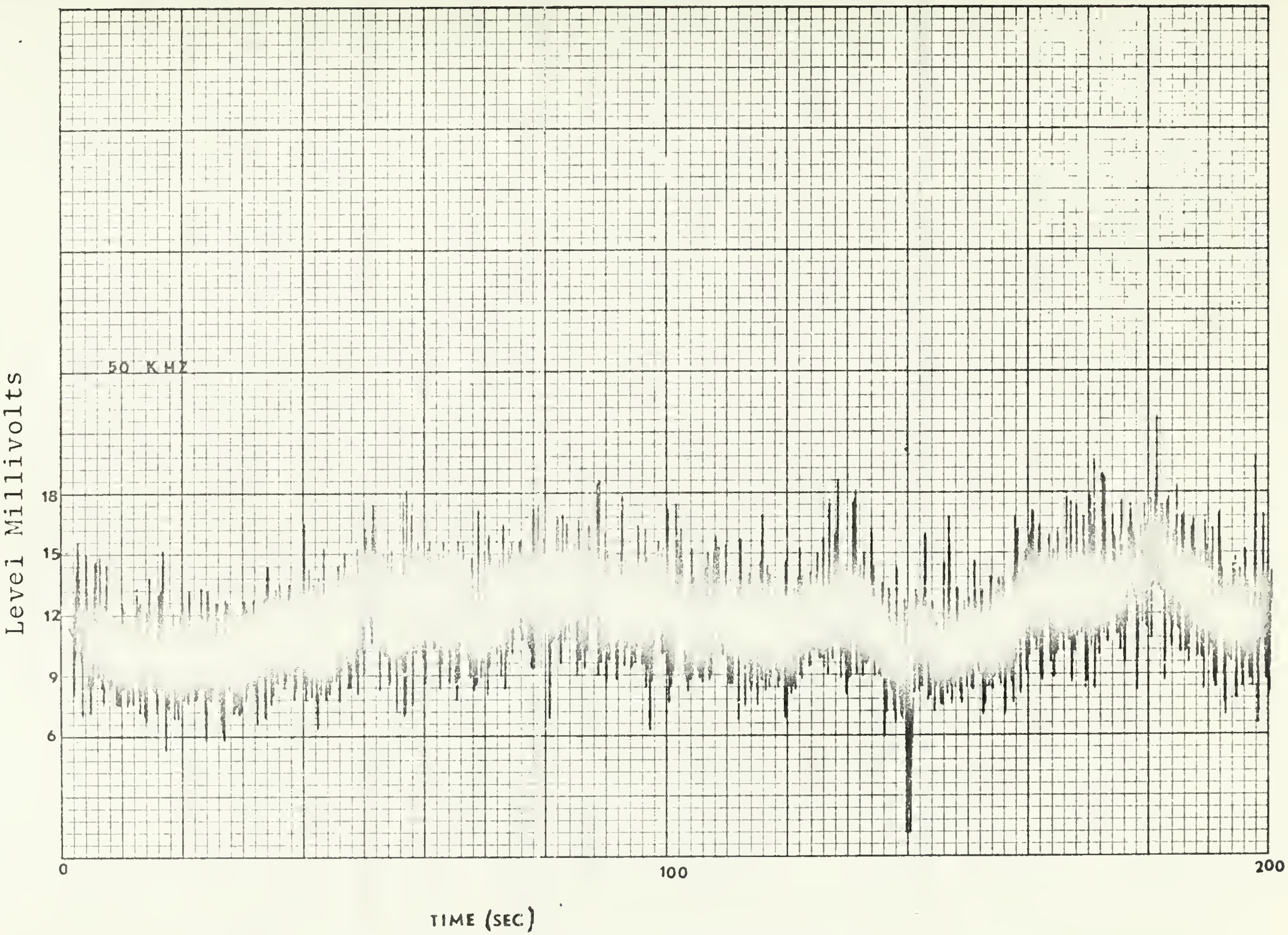

Figure 47. Level change at 50 kHz under ice cover.

or induced by movement of floes along the shore acts as broadband impulsive source.

Figure 48 shows spectrum levels observed on 15 and 19 April 1971 which are typical open water spectra for Cape North. The curve for 3 September is an open water spectrum reduced by NOL personnel. The lower levels in the range 70 to 300 Hz may reflect the change in propagation conditions for sound originating in the highly stratified conditions present in September. Typical wind dependence was observed above 1,000 Hz. The 3 September and 15 April plots were made when winds were 20 mph while wind speed for 19 April was 12 mph.

All traces indicated a broad maximum between 50 and 100 Hz. Spectra shape in this area follows curves produced by Wenz that showed the effect of distant ship traffic. Automobile and rail ferries regularly ply the route from Cape North to Newfoundland and these ships plus the normal merchant traffic in the Gulf of St. Lawrence were the most probable cause of distant traffic noises. The higher maximum observed on 19 April resulted from a small fishing vessel operating in the immediate area.

The pattern between 100 and 1,000 Hz indicates an area in which wind-dependent and non-wind-dependent sources interact to form a composite noise spectrum. The gentle slope between 100 and 200 Hz indicates that ship traffic is a predominant source in this region, while a gradual transition to a purely wind-dependent spectrum is observed from

200 to 1,000 Hz. This data supports Wenz's thesis that dependence of ambient noise on winds and sea state normally decreases below 500 Hz and that highly variable non-wind-dependent sources are effective over the range 10 to 1,000 Hz [Ref 2].

Under-ice noise spectra (Figure 49) present no clearly defined regions. The high levels below 100 Hz still show the effect of distant ship traffic; this is reasonable considering the relative close proximity of the ferry tracks. Spectra slopes are normally less than those observed under open water conditions. Abrupt changes in slope were ascribed to the impulsive source mentioned previously. Wind conditions during 15 March were forcing the ice pack to move seaward and a one-mile lead was present along the coast. Ten tenths cover on February 22 accompanied by on-shore winds resulted in ridging that was associated with the higher levels in the high-frequency region.

The observed spectral ranges for open water and ice cover conditions are presented in Figures 50 and 51. Comparative data for the range 40 to 1,100 Hz was provided by Dr. F. A. Payne of DREA. The highest noise levels experienced under conditions of ice cover correspond to the lowest levels for open water conditions below 2 kHz. This indicates the major importance of wind and sea as sources of ocean noise. Above 2 kHz under-ice spectrum levels fall off less rapidly than do open water spectra, so that at 20 kHz, under-ice noise levels are generally above open water levels.

Although correlation plots were not made as a part of this study, there was an obvious lack of correlation between spectrum levels in different frequency ranges. Extreme levels in one region were not associated with extreme levels in another region. Such evidence supports the thesis that although the noise spectrum is continuous, separate sources dominate adjacent regions.

Spectrum levels below 40 Hz were not determined as a part of the present study. However, a recurrent high-amplitude component with a frequency range from from 15 to 20 Hz was observed during recording sessions. The levels of this signal was sufficient to cause overloading of the discriminators. To avoid this condition, the system gain was reduced until system overload was not apparent. A high-pass filter with an auxiliary amplifier was inserted between the discriminator and tape recorder to boost the filtered signal to acceptable record levels. Visual observation of ice movement indicated that the 20-Hz signal was related to reversals of tidal currents. This observation, coupled with the extreme topographic variations near Cape North and in the Cabot Strait, suggests pressure fluctuations caused by turbulence in the water column as a possible source. Wenz [Ref. 2] cites experimental evidence that demonstrates oceanic turbulence induces large pressure fluctuations below 10 Hz, which in some instances are evident in the frequency range 10 to 100 Hz.

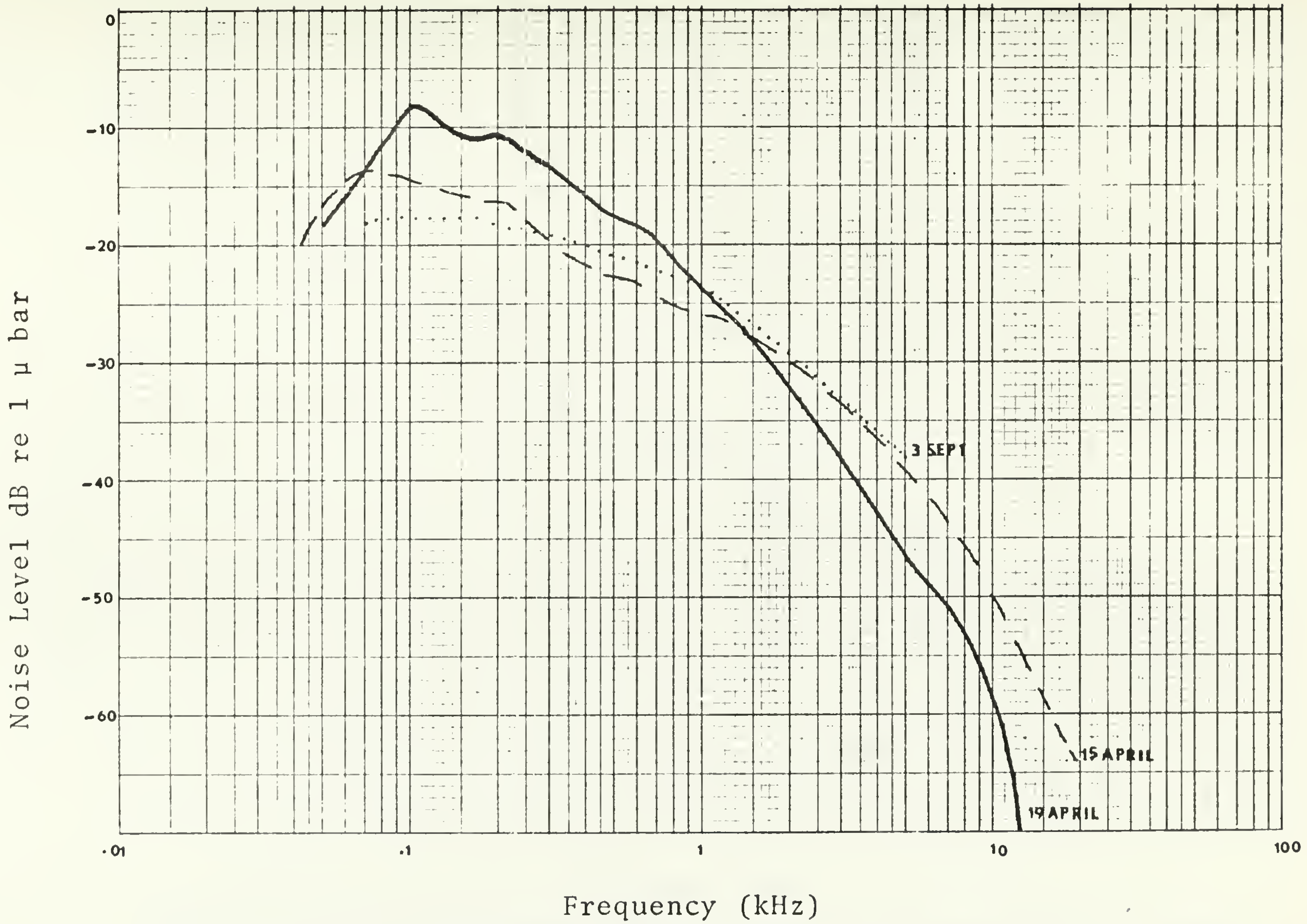

Figure 48. Noise spectra for open water conditions.

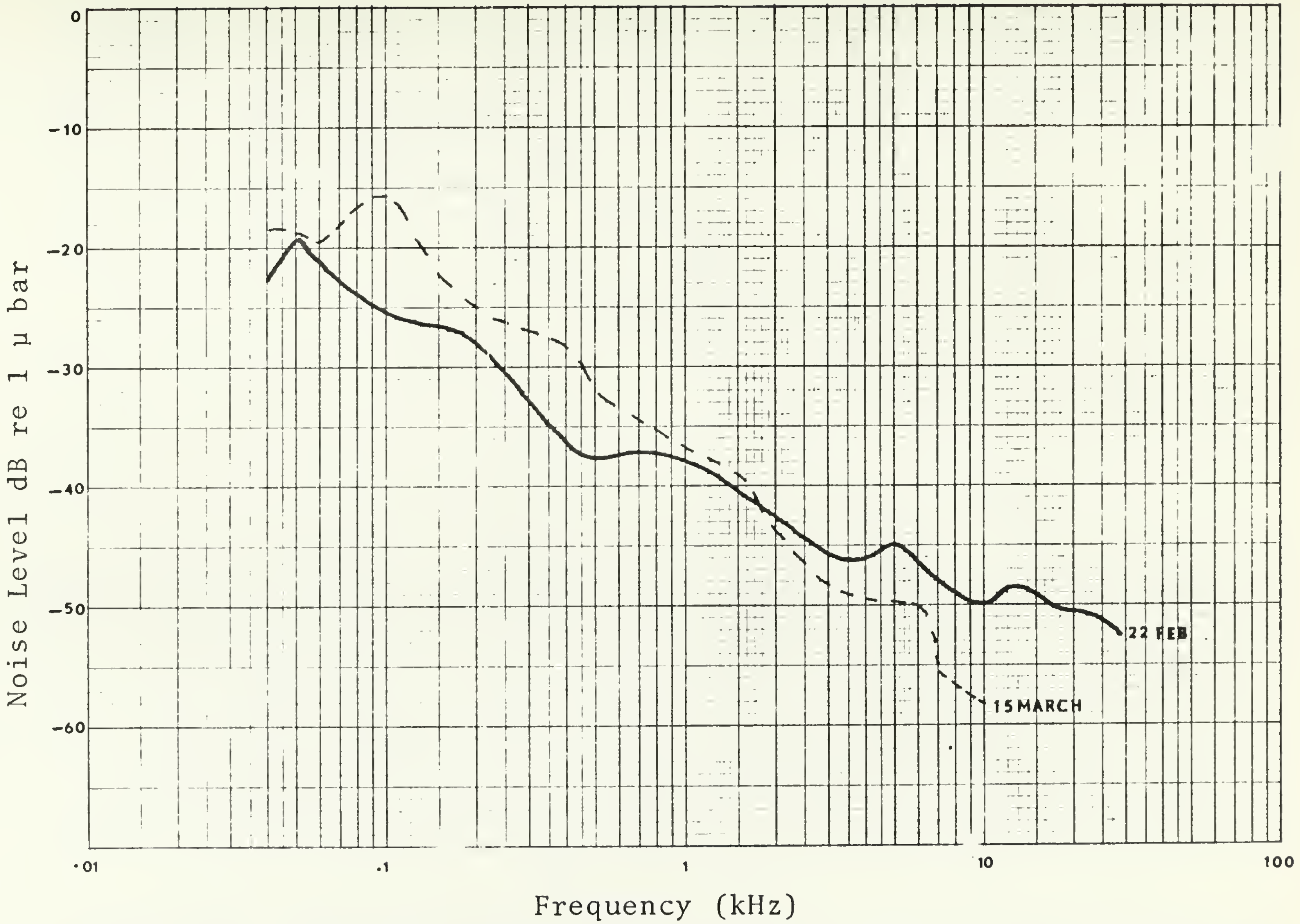

Figure 49. Typical noise spectra under conditions of ice cover.

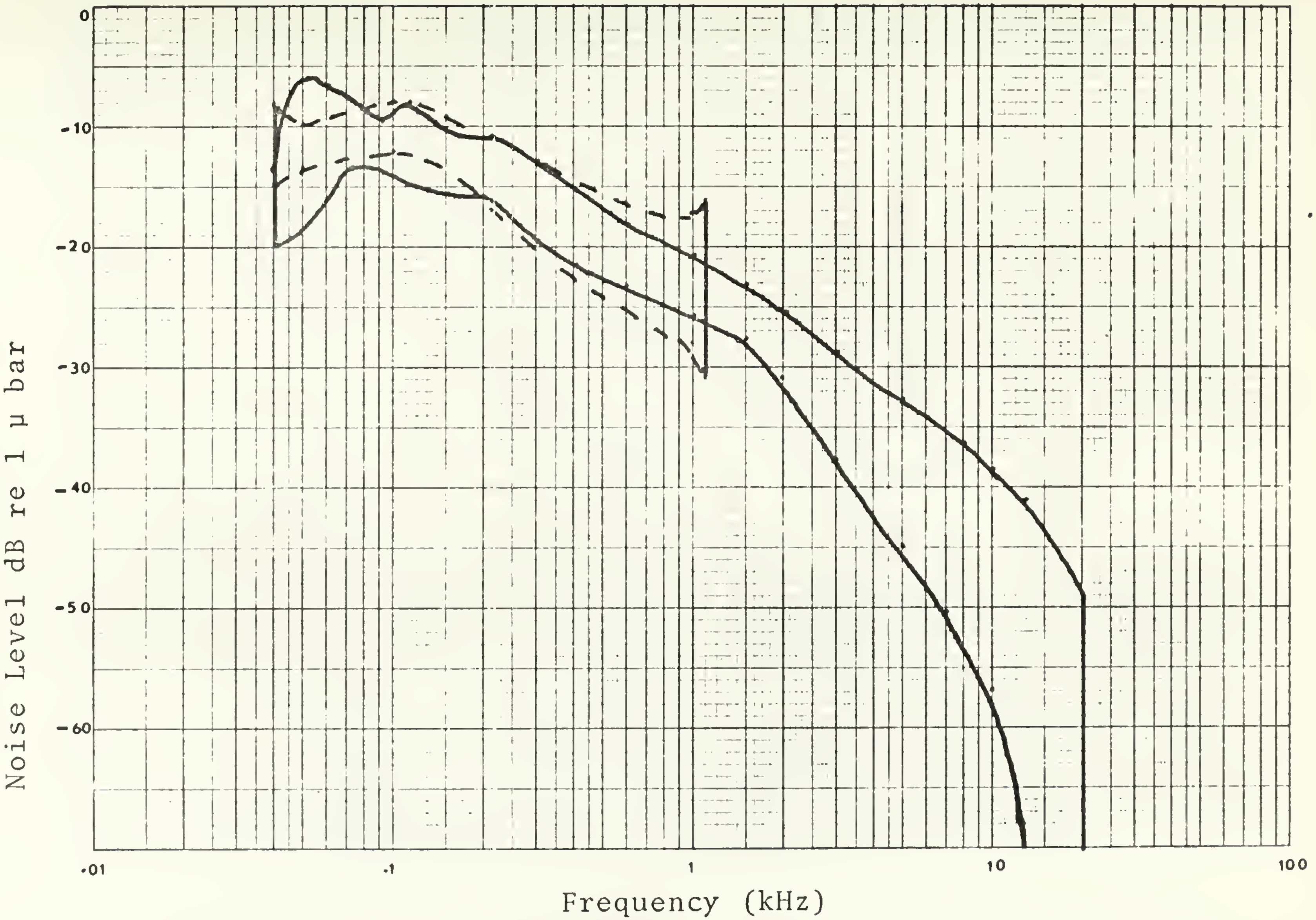

Figure 50. Range of noise spectrum levels for open water conditions. Dashed lines plotted from information provided by Dr. F. A. Payne.

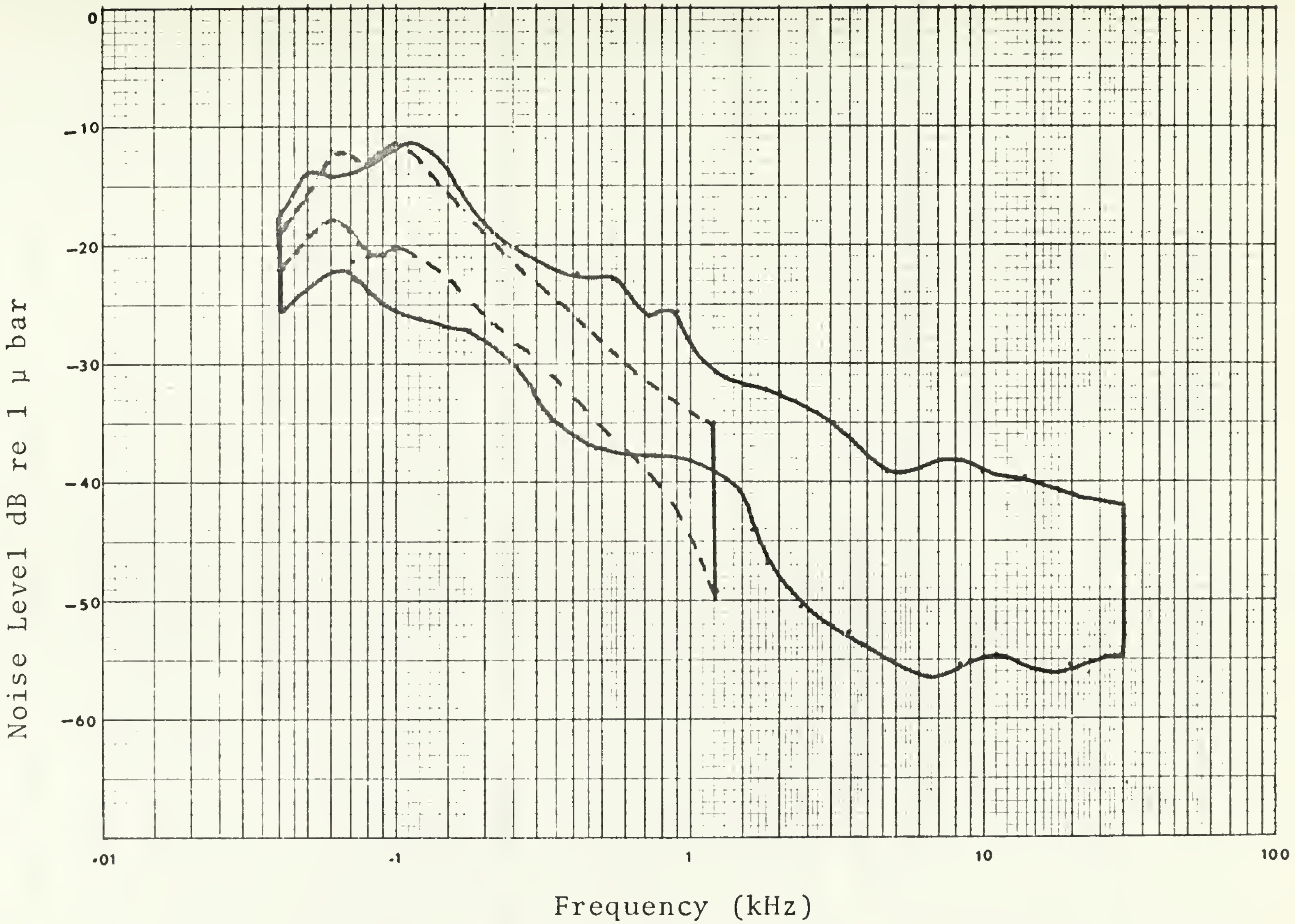

Figure 51. Range of noise spectrum levels under conditions of ice cover. Dashed lines plotted from information supplied by Dr. F. A. Payne

VII. SUMMARY AND CONCLUSIONS

The results of this study show that the NOL system was capable of responding to the range of ambient noise levels experienced under both open water and ice-covered conditions. However, interference by signals below 30 Hz required the use of high-pass filter not intended as a part of the instrument package. Since no system response curves for frequencies below 30 Hz had been prepared, it was not possible to determine quantitatively spectrum levels of the interference signals. The data were examined by wave analyzers that provided bandwidths ranging from 6 to 1,000 Hz. Frequency sweep rates, together with linear voltage outputs corresponding to 0, 17, 10, 100, 1,000 Hz/sec, could be selected. These features offered sufficient flexability to permit several methods of investigation to be carried out with little change-over time required.

Open water noise spectra observed at Cape North in 65 fms correspond to the deep water spectra shape proposed by Wenz (1962) rather than the shallow water spectral shapes found on the Scotian Shelf by Piggott (1964) or in the Gulf of St. Lawrence north of Prince Edward Island by Payne (1964). The shallow water spectra indicate a wind dependence at all frequencies above 20 Hz. Wind dependence does not become predominant in the Cape North spectra below 500 Hz. However, open water noise levels were 8 to 10 dB higher than Wenz's

profile for sea state three. More uniform sound propagation conditions during the winter may account for this difference. The close proximity of a heavily traveled ferry route and normal merchant traffic transiting the Cabot Strait account for the persistent ship traffic noise.

The most obvious effect of ice cover was the decrease in spectral energy levels below those observed for open water conditions. The highest under-ice noise levels experienced at Cape North below 2 kHz correspond to the lowest levels observed under open water conditions. For example, the lowest open water noise level observed at 100 Hz was -14 dB re 1 μ bar, while the lowest observed under-ice noise level at the same frequency was -34 dB re 1 μ bar. There is no direct dependence of under-ice noise levels on wind speed. However, the ice pack near Cape North was never shore fast but moved constantly under the influence of prevailing winds. Payne (1964) reported that the greatest reduction in under-ice noise levels occurred at higher frequencies, but that high levels did occur in the region during ice rafting. The most prominant feature of under-ice noise observed during this study was the occurrance of high-amplitude frequency independent bursts of sound that elevated noise levels throughout the spectrum, particularly above 500 Hz. Impulsive noise sources were reported by Milne and Ganton (1970) to be associated with cracks generated by thermal stress under shore fast Arctic ice. Although not directly observed, it is proposed that the noise bursts

in the Cape North data originate from shear stresses set up by mechanical actions. The bursts were more pronounced under convergent ten tenths ice cover. Except for persistent ship noise, the generation of ambient noise beneath the sea ice in the vicinity of Cape North is controlled by relative motion within the ice field. This motion is induced by prevailing wind and current fields. The net effect of these mechanically induced sound bursts was to raise the noise level above comparable open water levels at all frequencies greater than 2,000 Hz.

The NOL system as presently configured is capable of monitoring the level and variability of underwater ambient noise. However, if a more quantitative cause and effect relationship is to be established, more precise determinations of environmental parameters is required. Appendix B contains a proposed plan for future investigations which, if adopted, could lead to an improved understanding of time rate of change in environmental variables.

APPENDIX A

TAPE INVENTORY

Date & Time	Tape # & Speed	Remarks
1500 29 Jan 1971	1 15 ips	Temp 15°F Wind 5 mph from SW Sky clear Ice young pack 1/2 mile offshore moving from east to west under influence of current. Inshore a few small floes and new ice formation This tape sent to ARL
1600 29 Jan 1971	2 15 ips	
1900 29 Jan 1971	Copy #3 15 ips	This was a calibration tape made for NOL Channel #1 - Voice #2 - ARL passive #3 - ARL active #4 - NOL HF #5 - ARL sync #6 - NOL LF bottom #7 - NOL LF top
2030 29 Jan 1971	4 15 ips	Temp 12°F Wind 8 mph from west Ice. The ice has moved inshore with only a few floes over the array Two ships visible
29 Jan 1971	Copy A 15 ips	Copy of tape made by L. Barber of ARL commentary on tape
0930 22 Feb 1971	A1 15 ips	Temp 16°F Wind 14 mph from NW Barometer 29.95 in Ice. 9/10 cover of new and grey white, some ridging with minor pressure ridges Large low-frequency signal monitored on HF channel

Date & Time	Tape # & Speed	Remarks
1030 22 Feb 1971	A2 30 ips	Temp 18°F rising Wind 14 mph from NW Bar. 29.95 steady Ice as in A1 Current .4 Kts Filter setting A1 then A4 to avoid pronounced LF component. Only HF channel recorded to determine if fm carry-over affected HF signal on previous tapes.
1430 22 Feb 1971	A3 15 ips	Temp 28°F falling Wind 5 mph from Nw veering to SW Bar. 29.0 falling Ice. 8/10 cover with numerous open leads Current .6 Kts Higher amplitude signal apparent on upper LF hydrophone
1540 22 Feb 1971	A4 30 ips	Temp 25°F Wind 8 mph from SW Bar 29.0 steady Ice as in A3, 18 to 24 inches thick in floes 3 to 4 inches in refrozen leads. Large LF component evident in filter settings A1 and A2
2230 22 Feb 1971	A5 15 ips	Temp 18°F Wind 8 mph from W gusting to 15 Bar. 29.88 rising Ice as in A3. Leads in the bay have refrozen but leads outside the Cape are open
1050 28 Feb 1971	A 60 ips	The first tape made by DREA staff. The label sets record speed as 30 ips but voice playback is understandable at 60 ips. This tape and the following four were recorded with fm electronics set for 30 ips but the record was operated at 60 ips. Temp 42°F Wind 20 to 40 mph from S to SW Bar. 29.40 Ice. Main pack 10 miles offshore.

Date & Time	Tape # & Speed	Remarks
28 Feb 1971	B	Three tapes were recorded on this date. Approximately five minutes of data were taken at each filter position for the high-frequency channel, A1 through 5; switches B and C were set at positions 4 and 5 respectively. Tape A has filter positions 1 and 2. Tape B has filter positions 2, 3 and 4. Tape C has filter positions 4 and 5 plus calibration and self-noise signals. The labels all state record speed as 30 ips but voice playback is understandable at 60 ips. FM electronics were set for 30 ips.
28 Feb 1971	C	
1100 2 March 1971	1	Tapes 1 and 2 were also recorded at 60 ips with electronics set for 30 ips. Commentary on tapes.
1115 2 March 1971	2	
1145 2 March 1971	3 30 ips	The large-amplitude, low-frequency signal was evident on all channels.
1127 6 March 1971	1 30 ips	Temp 22°F Wind 25 to 30 mph from W Bar. 29.2 Ice extended from shore to 11/2 miles, then open water. A system-generated 25 kHz signal present in noise signal of HF channel.
6 March 1971	2 30 ips	Commentary on tape
1645 7 March 1971	Reel 1 30 ips	Commentary for tapes 1 and 2 made by DREA is on the tape.
2200 7 March 1971	Reel 2 30 ips	

Date & Time	Tape # & Speed	Remarks
15 March 1971	Reel 1 and 2 30 ips	Temp 41°F Wind 18 mph from S Bar. 29.6 falling Ice. Except for scattered floes in the Bay, the main pack was 11/4 miles offshore. The amplifier for the high-frequency channel remained in position B2 throughout both these tapes. Only low-frequency channels were analyzed.
17 March 1971	1 and 2 30 ips	Commentary on tapes.
1420 22 March 1971	Reel 1 and 2 30 ips	Commentary on tapes.
0940 27 March 1971	Reel 1 and 2 30 ips	Temp 30°F Wind Calm Ice. Large floes in loose pack Bar. 30.2 The ARL system was operated during this recording session.
1340 30 March 1971 1410 30 March 1971	Tape A 30 ips Tape B 30 ips	Temp 40°F Wind 10 mph from W Bar. 29.5 rising Ice. Bay full to 2 miles offshore, then open water to the main pack at 6 miles. ARL system active during record session.
1430 15 April 1971	Tape D1A 30 ips	The tapes listed as D1A and D1B, etc., have the following channel arrangement: A tapes have Channel 1 LF Channel 2 HF Channel 3 Voice B tapes have Channel 5 LF Channel 6 HF Channel 7 Voice Temp 40°F Wind 10 mph from S decreasing Bar. 29.6 Open water. A Dynatronic Model 112 high-pass filter with a low-frequency cutoff at 40 Hz

Date & Time	Tape # & Speed	Remarks
		was inserted with an Ithaca Model 6064-54 inserted after the discriminator to avoid interference from the 20 Hz signal.
1900 15 April 1971	Tape D1B 30 ips	Temp 38°F Wind 20 mph from S gusting to 35 Bar. 29.53 Medium rainfall Current .7 Kts Filter system not used.
1430 16 April 1971	Tape D2A 30 ips	Temp 38°F Wind 18 mph from SE Bar. 29.9 Current .3 Kts Filter system as for D1A. Two fishing vessels operating in the area.
1900 16 April 1971	Tape D2B 30 ips	Temp 36°F Wind 15 mph from S Bar. 29.95 Current .2 Kts Filter system in use. One Coast Guard vessel in visual range.
0830 17 April 1971	Tape D3A 30 ips	Temp 41°F Wind 10 mph from E Bar. 29.85
0930 17 April 1971	Tape D3B 30 ips	Filter system used for D3A and removed for D3B. Low-frequency component faded near the end of recording session.
1200 17 April 1971	Tape D4 30 ips	Temp 41°F Wind 15 mph from E Bar. 29.8 NOL and ARL systems operating.

NOTE: Unless otherwise stated, normal channel selections are as follows:

Channel 1 LF
Channel 2 HF with am electronics
Channel 3 LF
Channels 4, 5 and 6 ARL system
Channel 7 Voice

APPENDIX B

PROPOSED INVESTIGATION PLAN

Section III details the wide variation in temperature and salinity that occurs in the vicinity of Cape North over a yearly cycle. These two factors determine in large part the sound velocity profile. The predominant efflux of fresh water at the surface and influx of salt water near the bottom modified by diurnal tidal currents may combine with extreme variations in bathymetry to cause turbulent pressure fluctuations at a bottom-mounted hydrophone. If cause and effect relationships are to be established between environmental source functions and ambient noise levels, these factors must be considered together with the wind field and ice cover.

Three field investigations spread over an annual cycle provide the substance of this proposal. The first investigation should be conducted in late August when the summer cycle is at its peak. The equipment should be checked and calibrated during this period as well as obtaining at least three ambient noise samples. These samples should be coordinated with a 24-hour series of hydrographic stations to determine temperature, salinity and current variations in the vertical plane. The 24-hour period is proposed to ensure that the effects of tidal currents have been established. During ambient noise recording sessions, the ship should be

rigged for silent operation of, if this is not possible, she should steam out of the immediate area.

A similar series of noise samples and hydrographic stations should be conducted during late December or early January to establish the normal winter propagation conditions.

The main effort to gather under-ice ambient noise data should be expended during February, since a wide spectrum of ice cover is experienced during that month. Aerial photography of the local region would aid in identification of the amount and type of ice cover. A request for services should be channeled to the Ice Observation Service, Canadian Department of Environment, formerly Department of Transport.

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13. ABSTRACT

Ambient noise data was collected from bottom-mounted hydrophones in 65 fms of water near Cape North, Nova Scotia, from January to April 1971. Preliminary analyses indicate that generalizations made from data collected at other sites can be used in only the broadest sense to predict noise levels at Cape North. The open water spectral shapes resemble deep water spectral shapes proposed by Wenz (1962) rather than shallow water spectra found by Piggott (1964) at another location on the Scotian Shelf. Under-ice noise levels are below open water levels in the frequency range 40 Hz to 2 kHz, but above this frequency, mechanical noise sources within the ice pack elevate levels above those found under open water conditions.

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